TRANSIENT MIXING DRIVEN BY BUOYANCY FLOWS

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Mixing driven by buoyancy-induced flows is of particular interest to microgravity processes, as the body force that governs the intensity of flow fields can be directly controlled. We consider a model experimental system to explore the dynamics of mixing which employs two miscible liquids inside a cavity separated initially by a divider.
The two liquids are oriented vertically inside a rectangular cavity with constant width and height, and varying depths to approach a cubical configuration. The two miscible liquids can be sufficiently diluted and died, for example water and deuterium oxide, such that a distinct interface exists across the divider. The transient mixing characteristic of the two fluids is addressed by following the Lagrangian history of the interface for various aspect ratios in the z-plane (depth variation) as well as a range of pulling velocities of the divider.

The mixing characteristic of the two fluids is quantified from measurement of the length stretch of the interface using image processing techniques. Scaling analysis shows that the length stretch depends on four governing parameters, namely the Grashof number (Gr), Schmidt number (Sc), aspect ratio (Ar), and Reynolds number (Re). We fix the Grashof number as well as the Schmidt number. Thus our problem reduces to a co-dimension two bifurcation in parametric space for Ar and Re.

Our experimental results show that for Gr on the order of 10^6 and a nominal cavity aspect ratio Ar=0.2, the net effect of removal of the divider and the overwhelming buoyancy force causes an overturning motion which stretches and fold the interface to produce an internal breakwave. The structure of the breakwave is similar to the ubiquitous Rayleigh-Taylor instability morphology. The breakwave is dissipated either through internal or wall collision depending on the impulsive velocity of the divider as prescribed by the Reynolds number. The decay of the collision event occurs through sloshing oscillations over a short time scale. The two fluids then become stably stratified with a diffusive band at the interface indicating mass transport.

The local bifurcation of the internal breakwave is investigated as a function of aspect ratio. Results show that for narrow cavities on the order of 2mm (Ar=0.04), folding does not occur the interface only stretches. As the cavity size increases folding occurs through a supercritical bifurcation. Insight into the mechanism of folding is obtained from measurement of the flow field using Particle Imaging Velocimetry. These results show that in the neighborhood of the folding event, there exists hyperbolic points in the flow caused by multiple vortex interactions. The global stretch of the interface as a function of time is nearly Gaussian; calculations of finite-time Lyapunov exponents as well as construction of horseshoe maps indicate the likelihood of a chaotic transient.

Transient Mixing Driven By Buoyancy Flows

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ABSTRACT

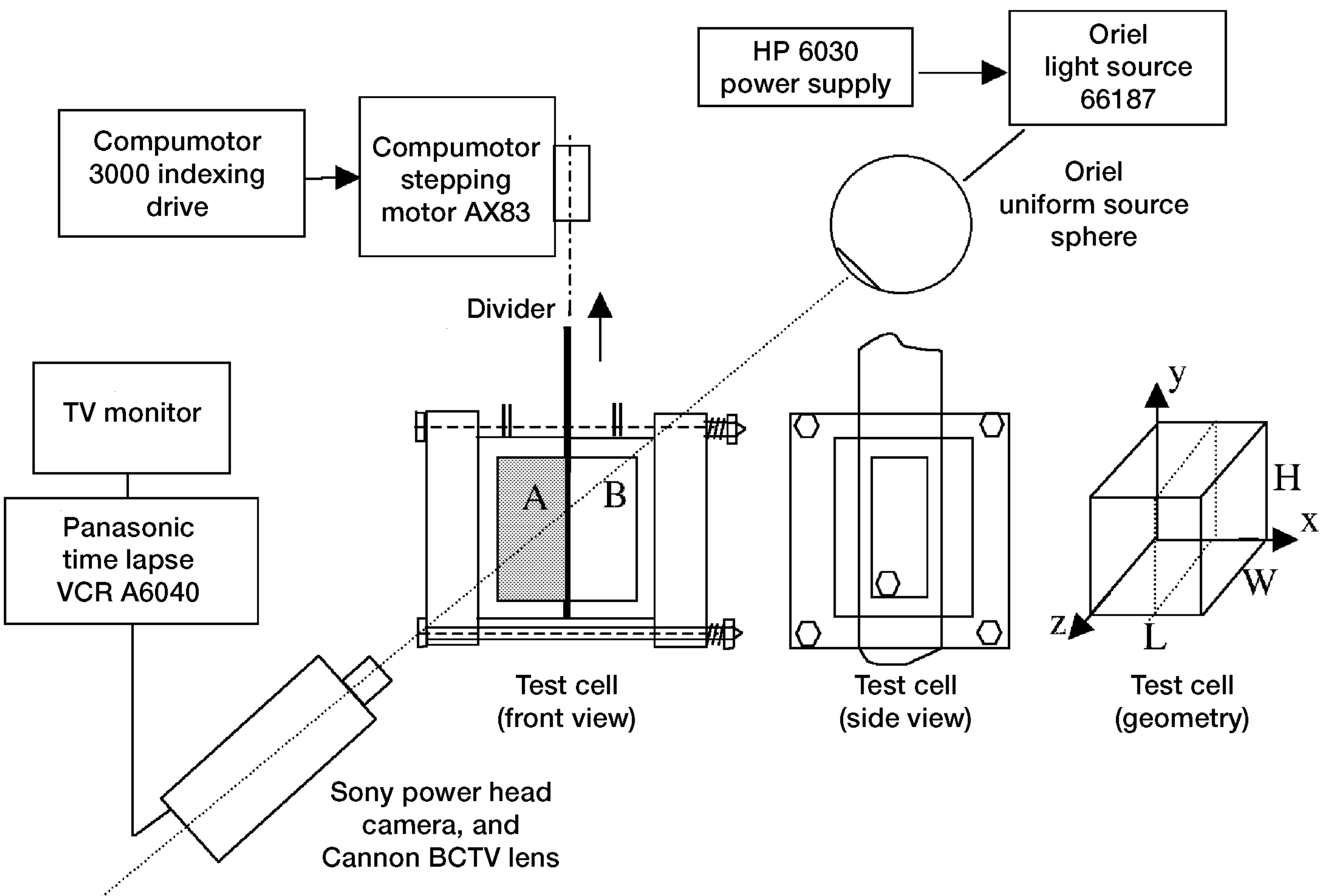
Mixing driven by buoyancy-induced flows is of particular interest to microgravity processes, as the body force that governs the intensity of flow fields can be directly controlled. We consider a model experimental system to explore the dynamics of mixing which employs two miscible liquids inside a cavity separated initially by a divider. The two liquids are oriented vertically inside a rectangular cavity with constant width and height, and varying depths to span the range of a Hele-Shaw cell to a 3-D configuration. The two miscible liquids can be sufficiently diluted and died, for example water and deuterium oxide, such that a distinct interface exists across the divider. The transient mixing characteristic of the two fluids is addressed by following the Lagrangian history of the interface for various aspect ratios in the z-plane (depth variation) as well as a range of pulling velocities of the divider.

The mixing characteristics of the two fluids are quantified from measurement of the length stretch of the interface and its flow field using respectively image processing techniques and Particle Imaging Velocimetry. Scaling analysis shows that the length stretch depends on four governing parameters, namely the Grashof number (Gr), Schmidt number (Sc), aspect ratio (Ar), and Reynolds number (Re). Variation of the Schmidt number is taken into account through thermophysical property variation. Thus our problem reduces to a codimension three bifurcation in parametric space for Gr, Ar, and Re.

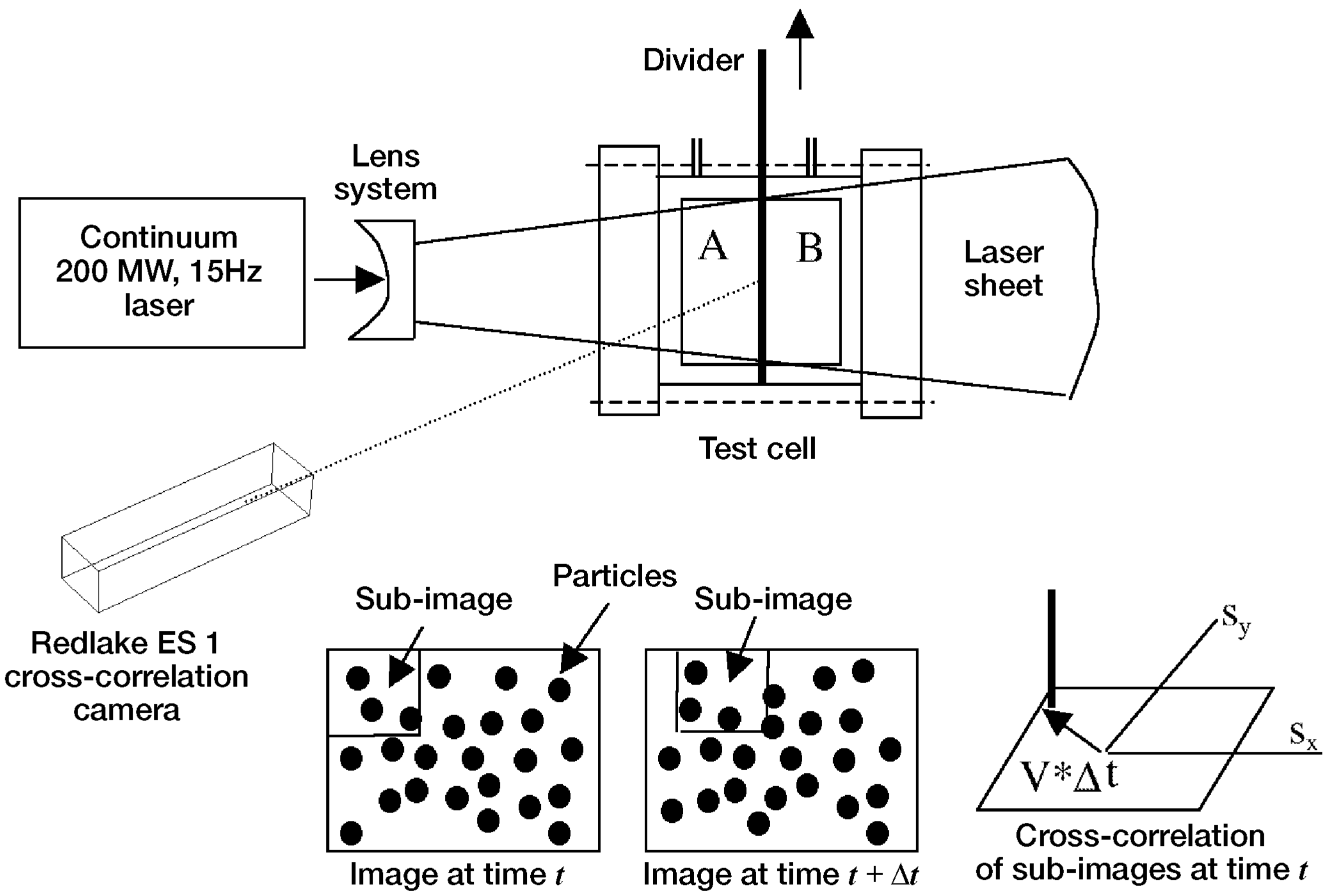
Our experimental results show that for Gr on the order of 10^6 and a nominal cavity aspect ratio Ar = 0.2, the net effect of removal of the divider and the overwhelming buoyancy force causes an overturning motion which stretches and folds the interface to produce an internal breakwave. The structure of the breakwave is similar to the ubiquitous Rayleigh-Taylor instability morphology. The breakwave is dissipated either through internal or wall collision depending on the impulsive velocity of the divider as prescribed by the Reynolds number. The decay of the collision event occurs through sloshing oscillations over a short time scale. The two fluids then become stably stratified with a diffusive band at the interface indicating local mass transport.

The local bifurcation of the internal breakwave is investigated as a function of aspect ratio. Results show that for narrow cavities on the order of 2mm (Ar = 0.04) folding does not occur, the interface only stretches. As the cavity size increases folding occurs through a supercritical bifurcation. Insight into the mechanism of folding is obtained from measurement of the flow field which shows that in the neighborhood of the folding event, there exists hyperbolic points caused by multiple vortex interactions. The global length stretch of the interface as a function of time is nearly Gaussian; calculations of finite-time Liapunov exponents as well as construction of horseshoe maps indicate the likelihood of a chaotic transient.

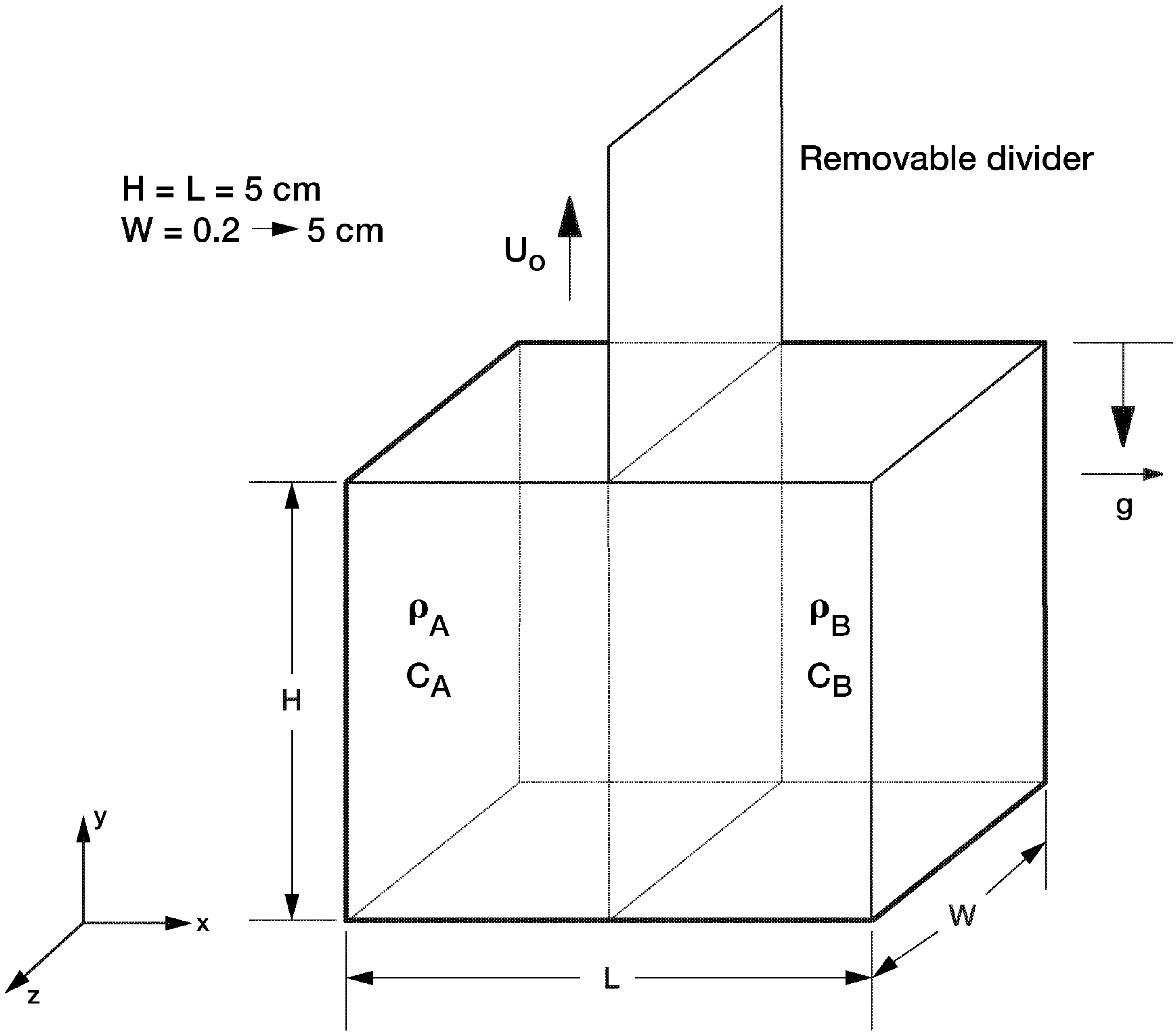
Experimental Set-up to Quantify the Interface Motion



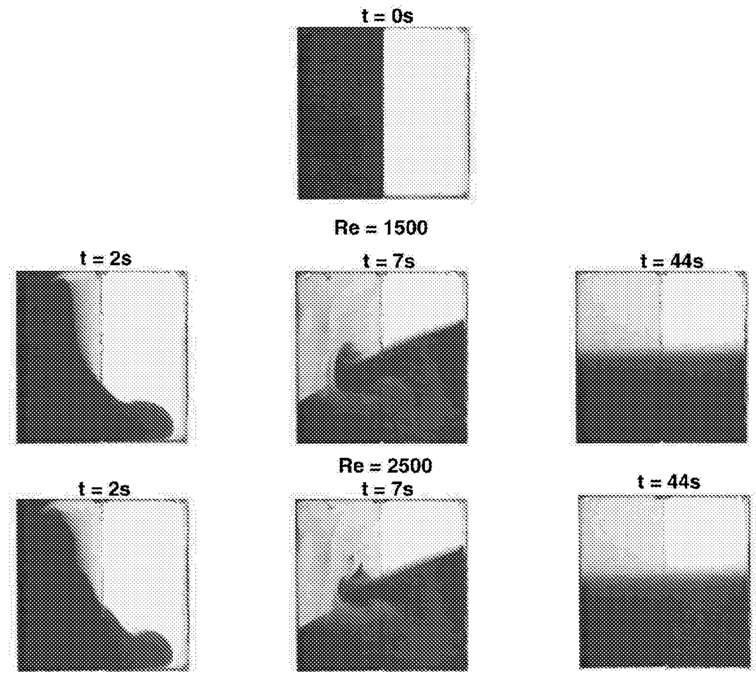
Experimental Set-up for Particle Imaging Velocimetry



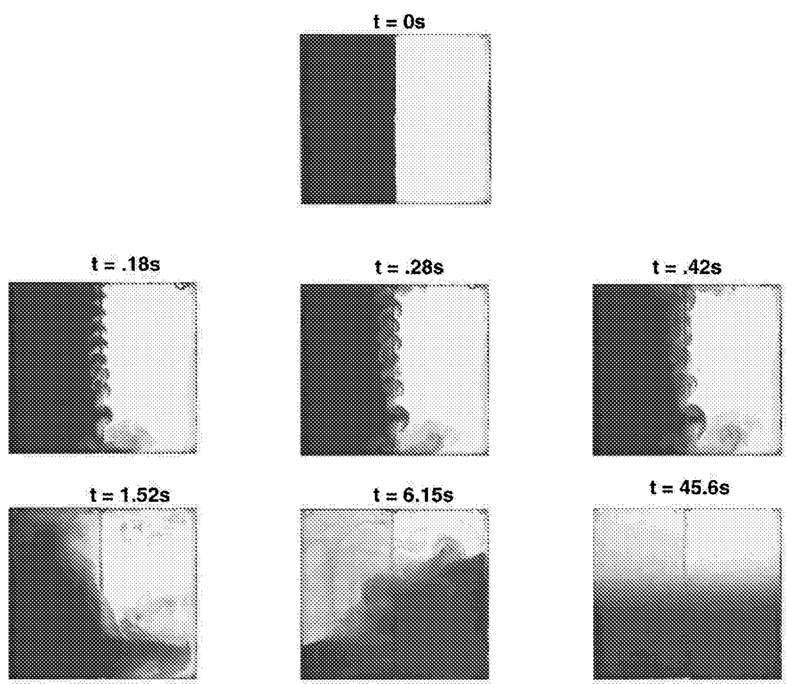
Initial Configuration of Two Fluids at Interface



Stretching and Folding of Interface During Mixing by Buoyancy-Induced Flow Field, Gr = 3.18×10^6, Ar = 0.2



Evolution of Kelvin-Helmholtz Instability Waves During Mixing Due to Impulsive Input Velocity, Gr = 3.18×10^6, Re = 2×10^4, Ar = 0.2



Parametric Range of Experiments

Case	Fluid A	Fluid B	S_A	S_B	ν_A $cm^2/\sec$	ν_B $cm^2/\sec$	$\frac{\Delta\rho}{\bar{\rho}}$	$\frac{\Delta\nu}{\bar{\nu}}$	Gr	Sc
1	H_2O+D_2O	H_2O+D_2O	0.9993	0.99925	0.01	0.01	0.00005	0.00	6.13×10^4	500
2	H_2O+D_2O	H_2O+D_2O	0.99965	0.9994	0.01	0.01	0.00025	0.00	3.06×10^5	500
3*	H_2O+D_2O	H_2O+D_2O	1.0023	0.9997	0.01	0.01	0.00259	0.00	3.18×10^6	500
4*	H_2O+D_2O	H_2O+D_2O	1.0215	0.9993	0.01	0.01	0.02197	0.00	2.69×10^7	500
5	H_2O+D_2O	H_2O+D_2O	1.0525	0.99925	0.01	0.01	0.05191	0.00	6.36×10^7	500
6*	$20\%Et.+H_2O$	$100\%H_2O$	1.026	0.9975	0.01158	0.01	0.02817	0.14643	2.96×10^7	1079
7	$40\%Et.+H_2O$	$100\%H_2O$	1.0505	0.9975	0.01316	0.01	0.05176	0.27288	4.73×10^7	1158
8	$20\%Pp.+H_2O$	$100\%H_2O$	1.013	0.9975	0.08598	0.01	0.01542	1.58325	8.20×10^5	4799
9	$20\%Et.+H_2O$	$20\%Pp.+H_2O$	1.026	1.013	0.01158	0.08598	0.01275	1.52522	6.56×10^5	4878
10	$40\%Pp.+H_2O$	$100\%H_2O$	1.026	0.9975	0.16196	0.01	0.02817	1.76739	4.67×10^5	8598
11	$20\%Et.+H_2O$	$20\%Pp.+H_2O$	1.026	1.0135	0.01158	0.08598	0.01226	1.52522	6.31×10^5	4878
12	$20\%Et.+H_2O$	$100\%H_2O$	1.026	0.9975	0.01158	0.01	0.02817	0.14643	2.96×10^7	1079

Microgravity experiments are denoted by *, Et. and Pp. denote ethylene-glycol and 1,2propylene-glycol

Parametric Space $\Lambda = \Lambda(Gr, Re, Ar, Sc)$

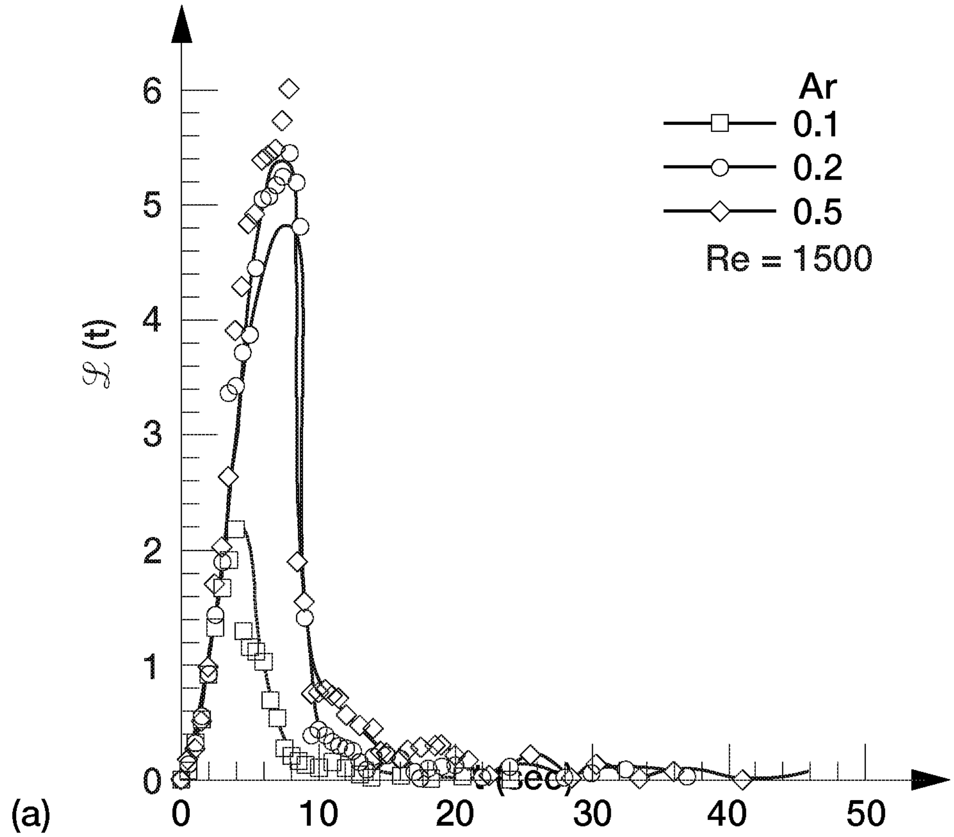
$$Gr = \frac{\Delta\rho}{\rho} \frac{n g_0 H^3}{\bar{\nu}^2}$$

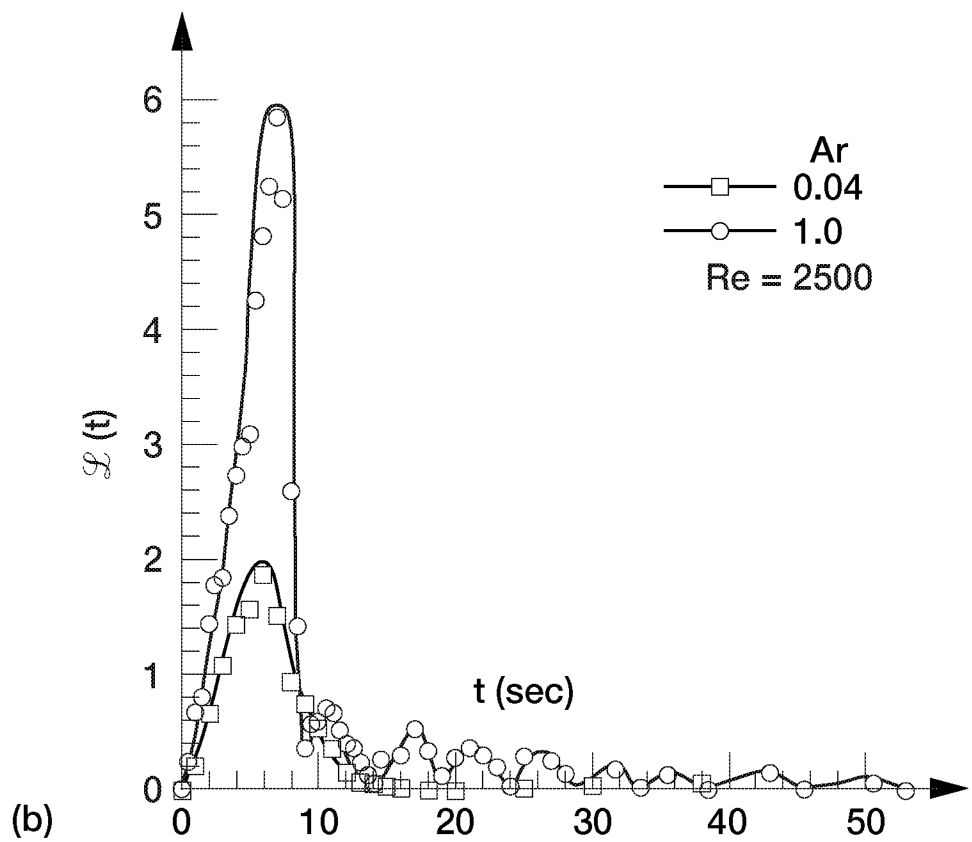
$$Re = \frac{U_0 H}{\bar{\nu}}$$

$$Ar = \frac{W}{H}$$

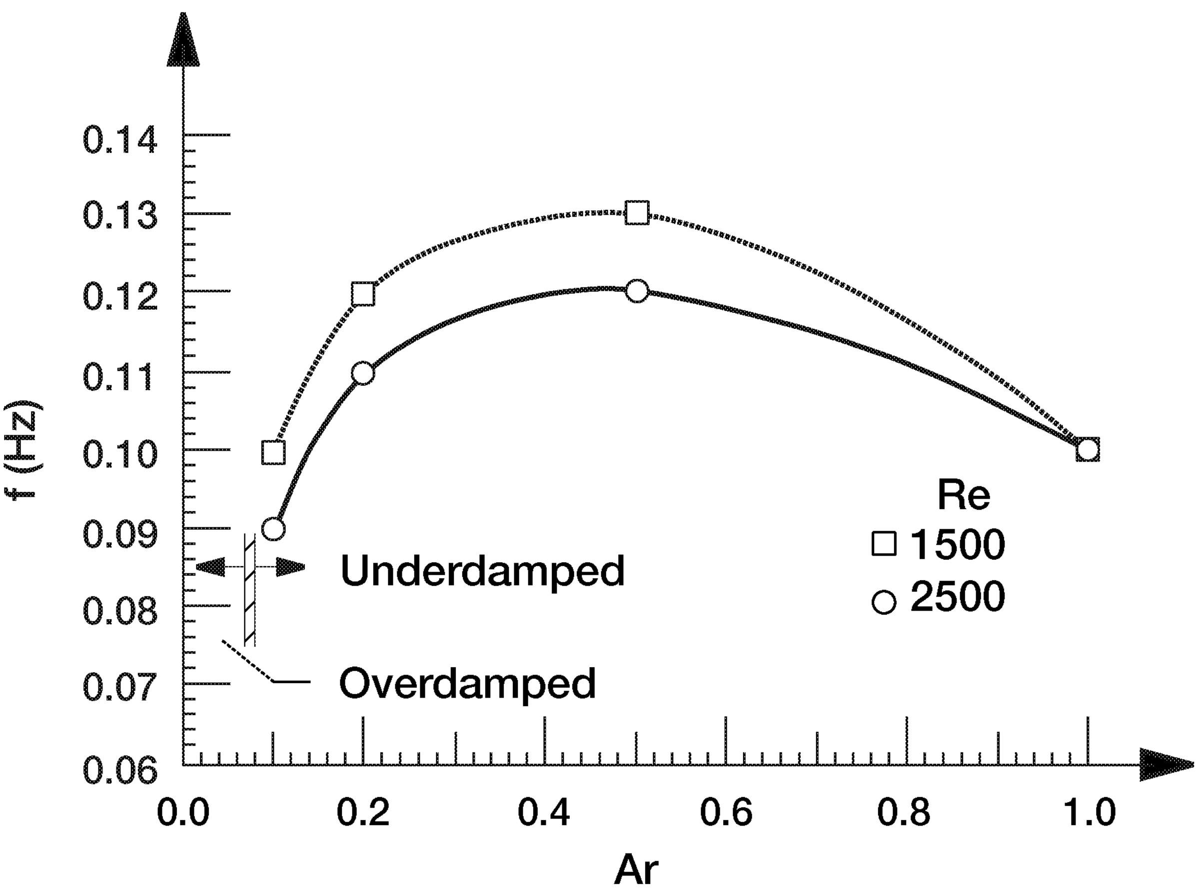
$$Sc = \frac{\bar{\nu}}{D_{AB}}$$

Length Stretch of Interface
Gr = 3.18×10⁶



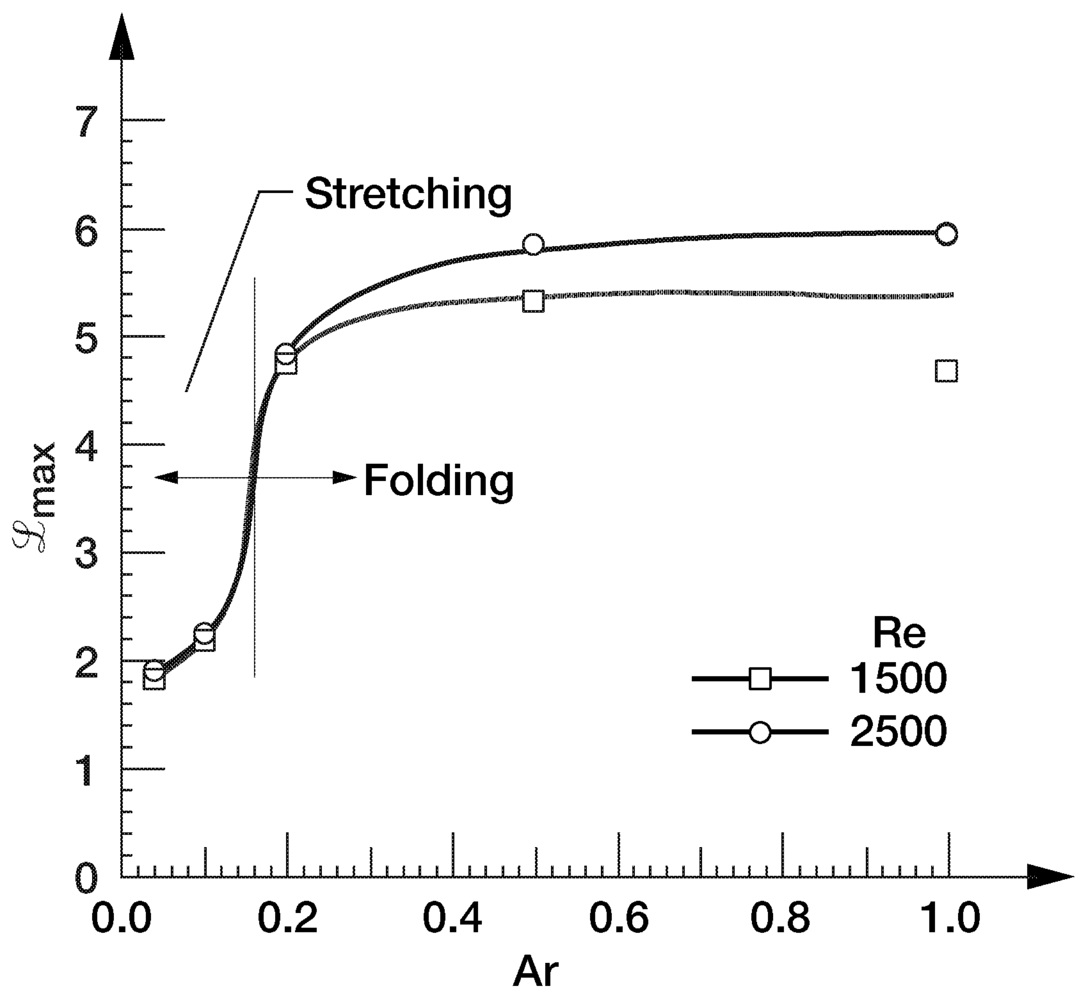


Decay Frequency of Sloshing Oscillations
Gr = 3.18×10^6



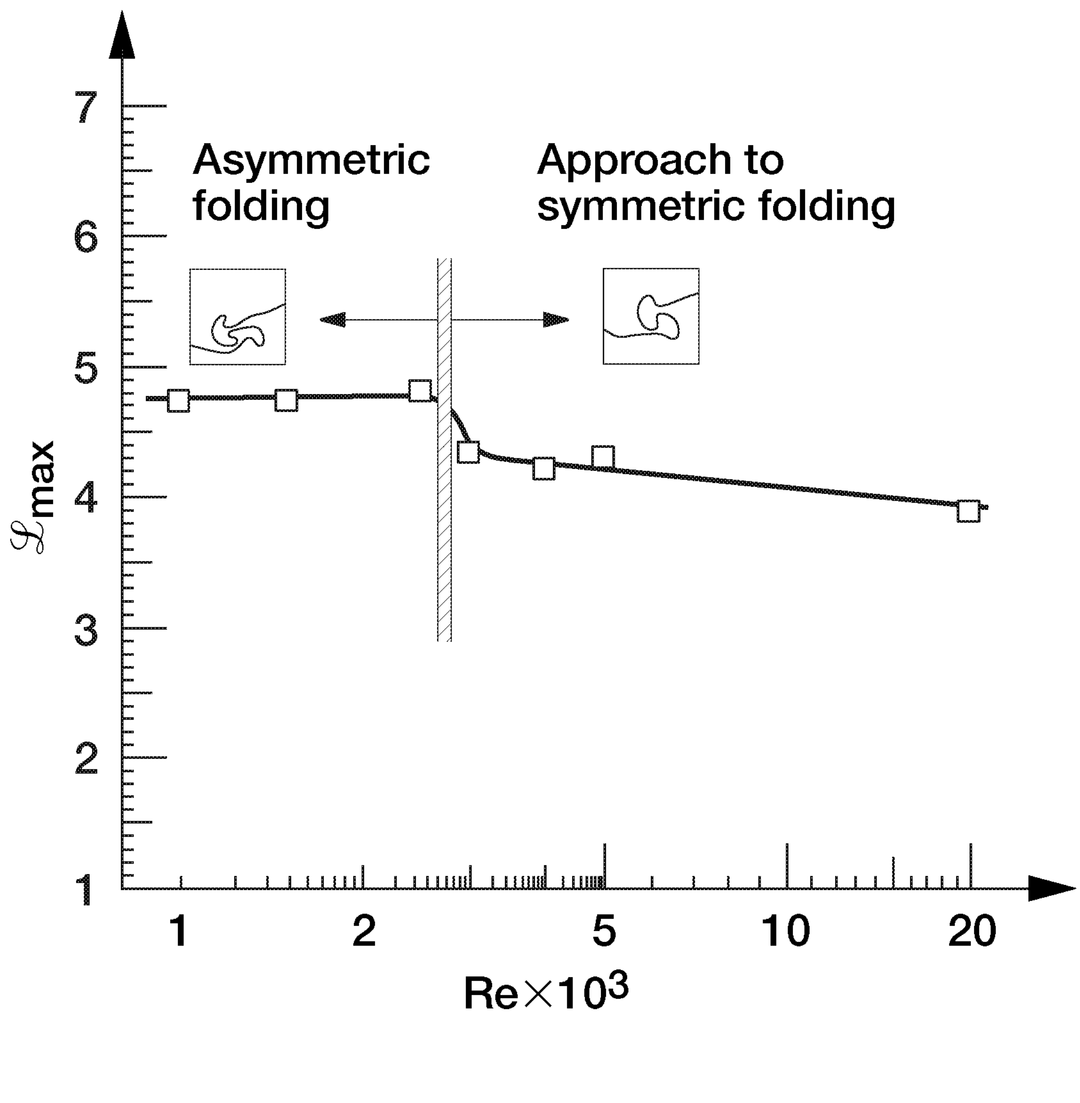
Bifurcation of Interface
Transition from Stretching to Folding

$Gr = 3.18 \times 10^6$



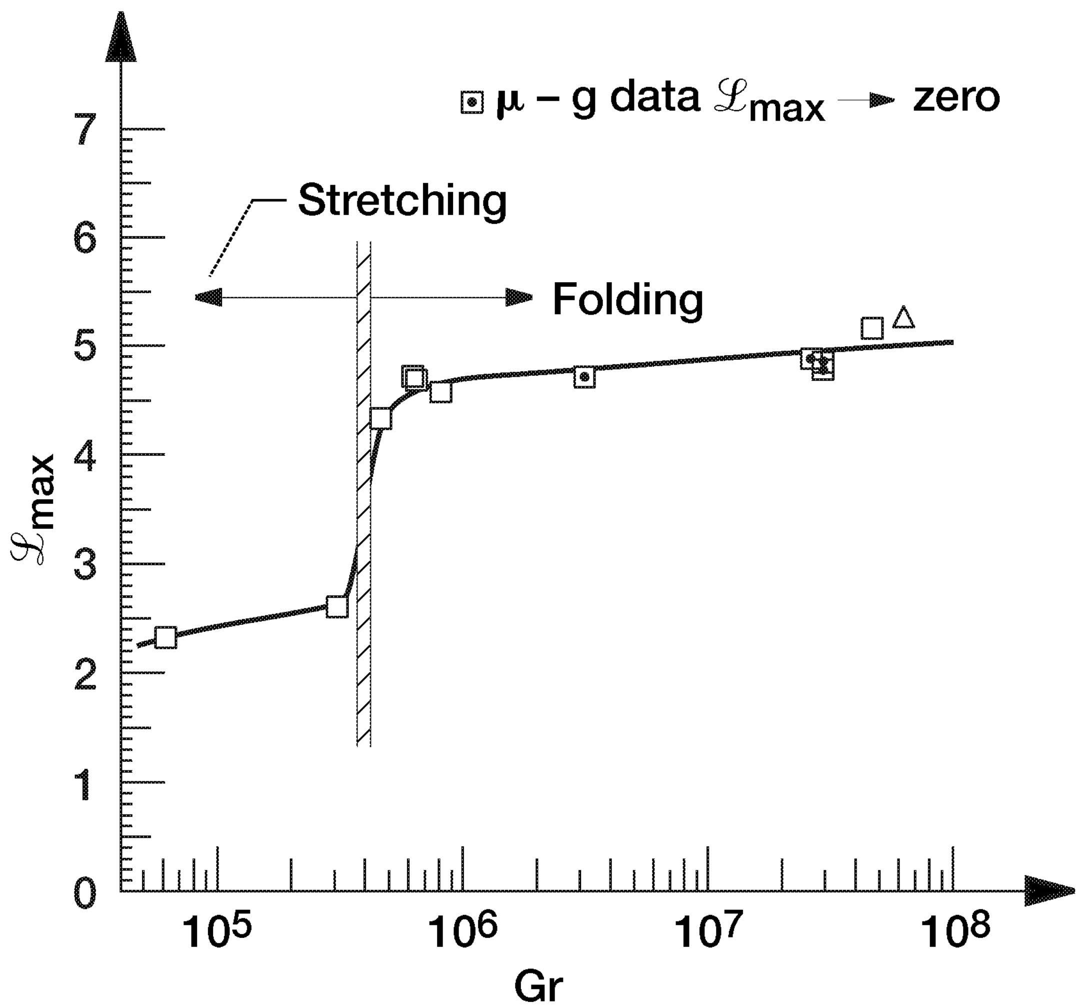
Effect of Impulsive Initial Velocity

Gr = 3.18×10^6, Ar = 0.2



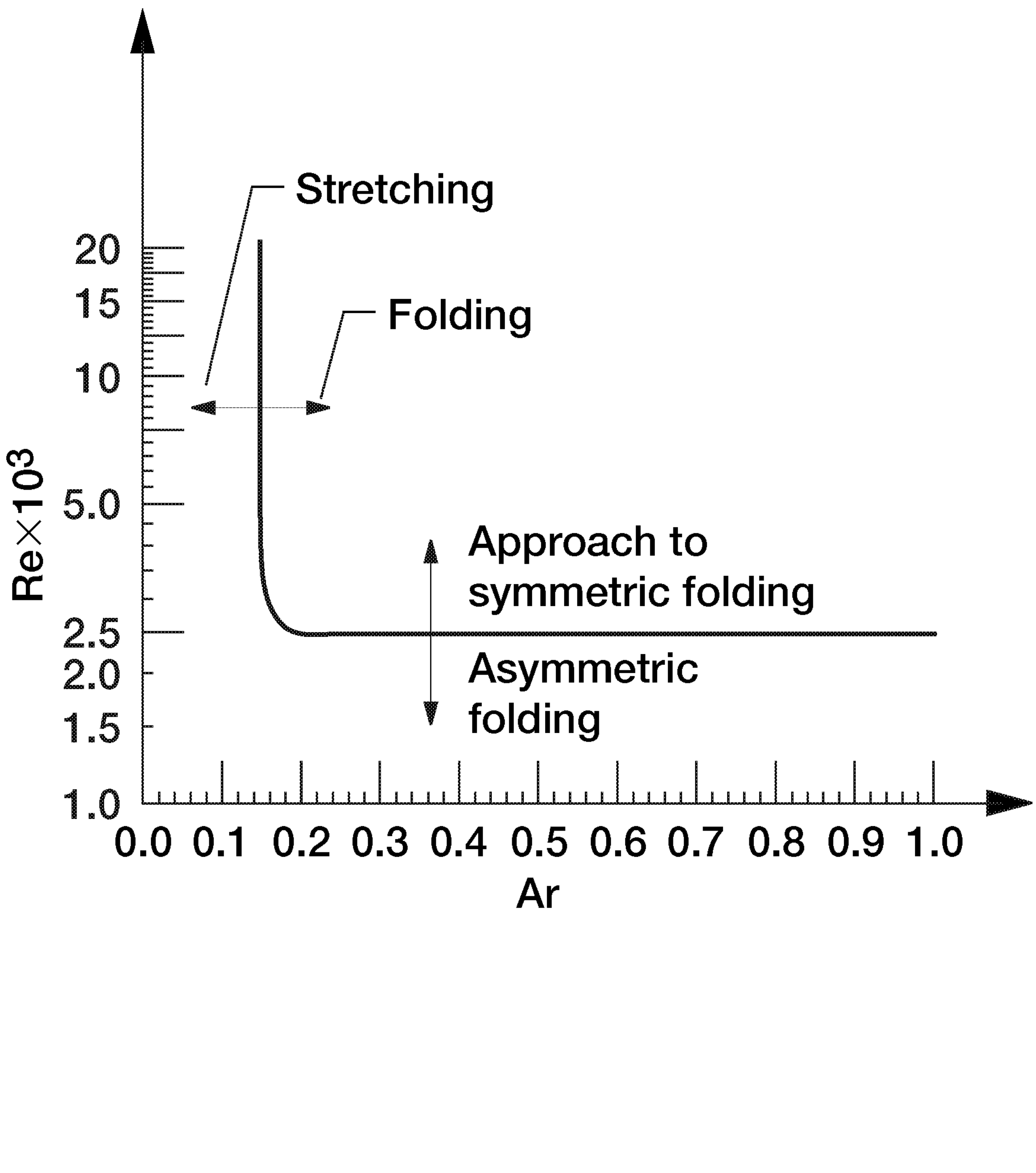
Bifurcation of Interface Due to Buoyancy-Induced Flow

Ar = 0.2, □ U_o = 5 cm/sec, △ U_o = 7 cm/sec

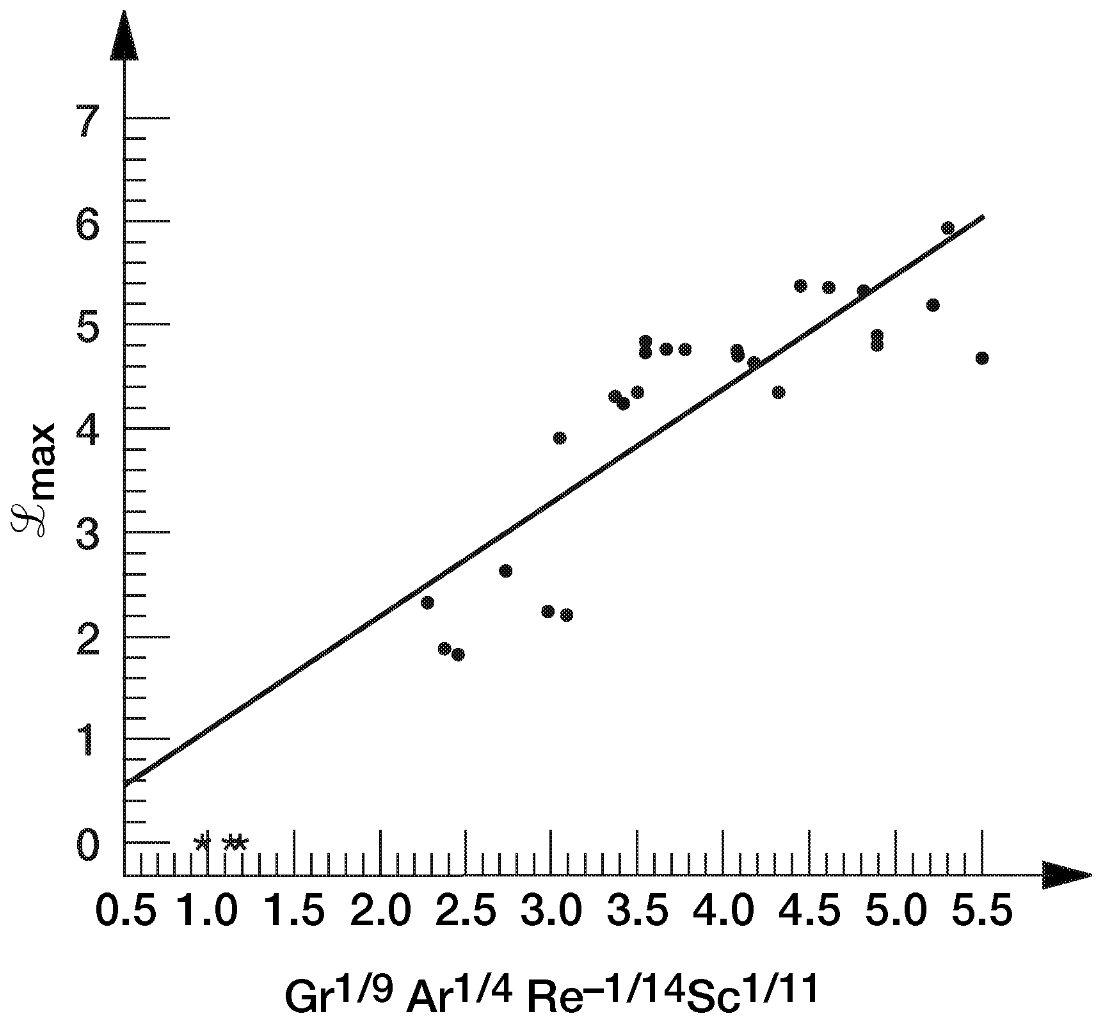


Stability Region of Interface Folding

$Gr = 3.18 \times 10^6$

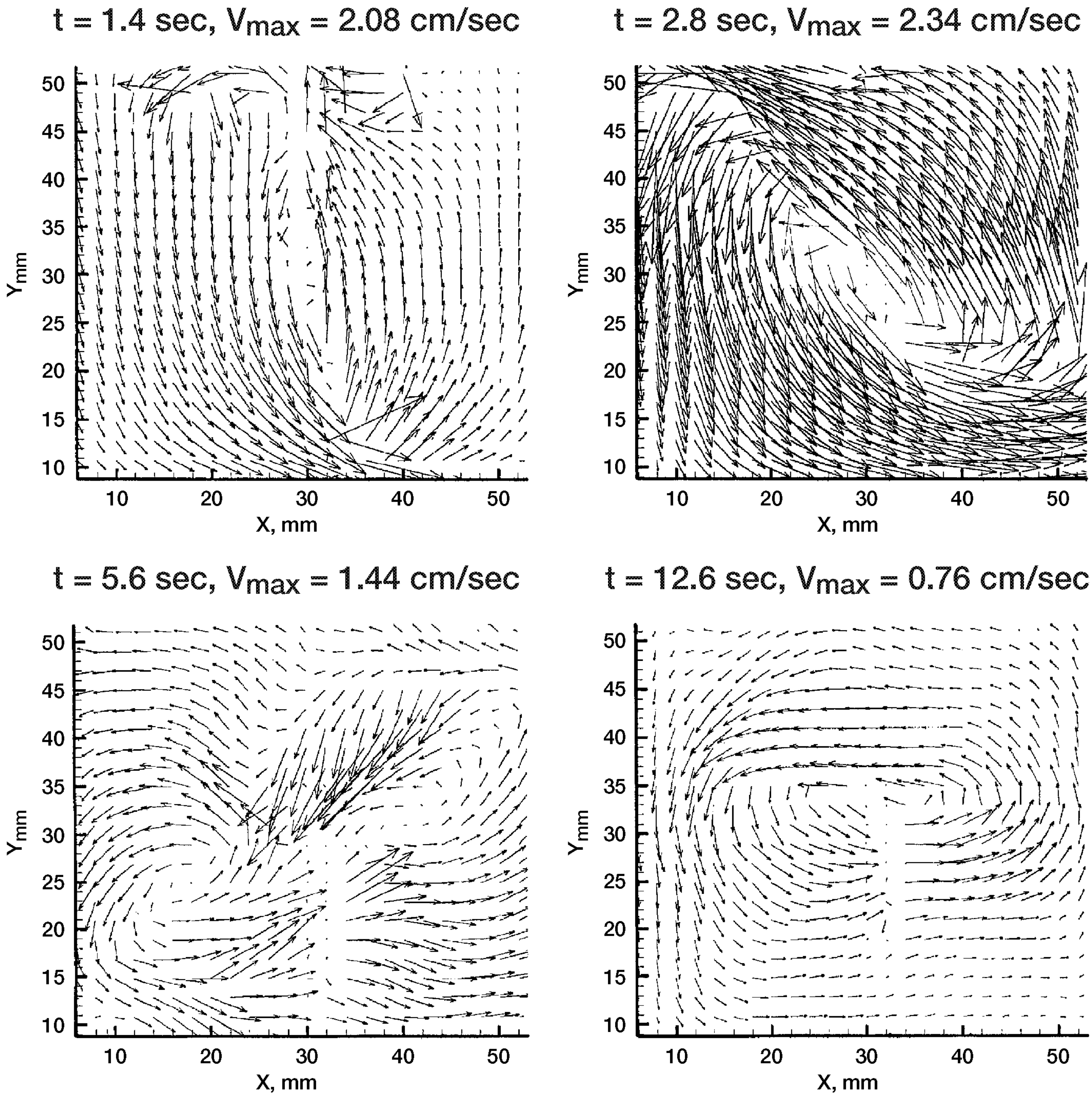


Correlation of Maximum Length
Stretch of Interface

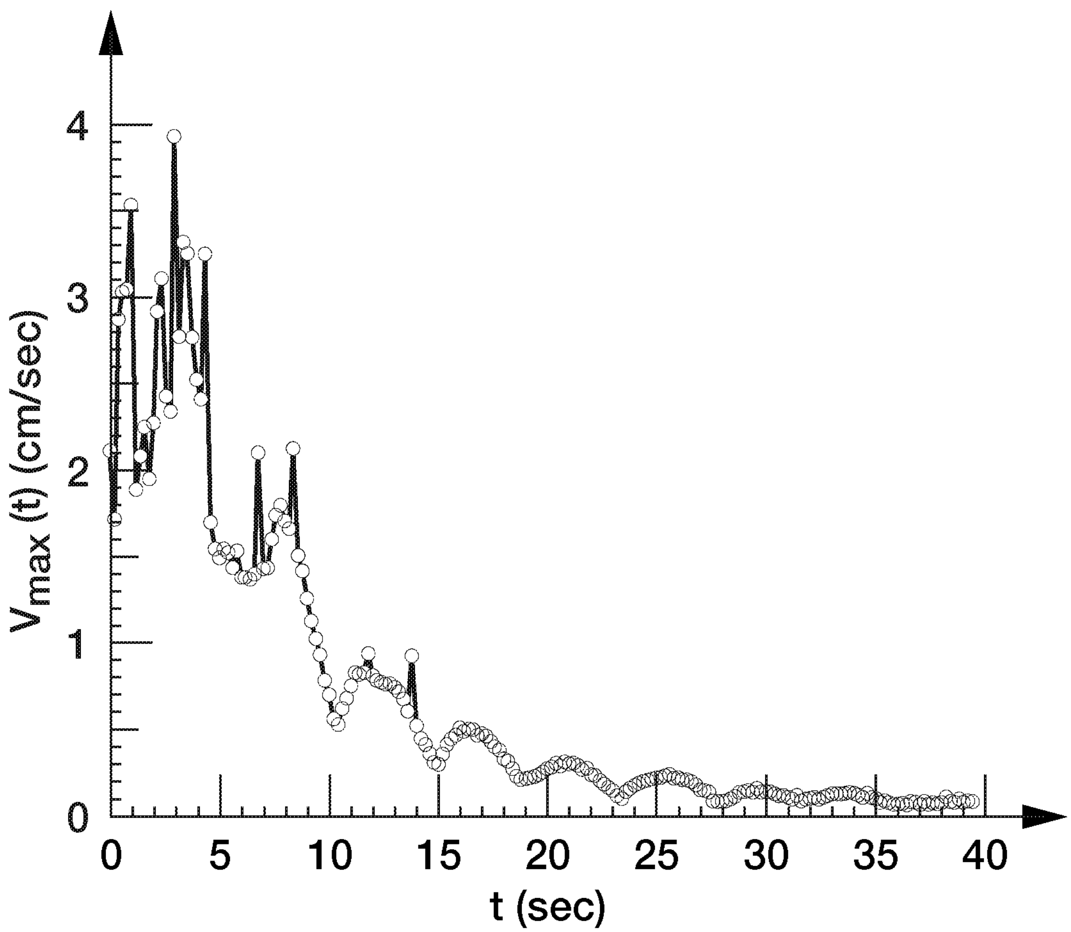


Flow Field Measurement
Using Particle Imaging Velocimetry

$Gr = 3.18 \times 10^6$, $Re = 1500$, $Ar = 0.2$

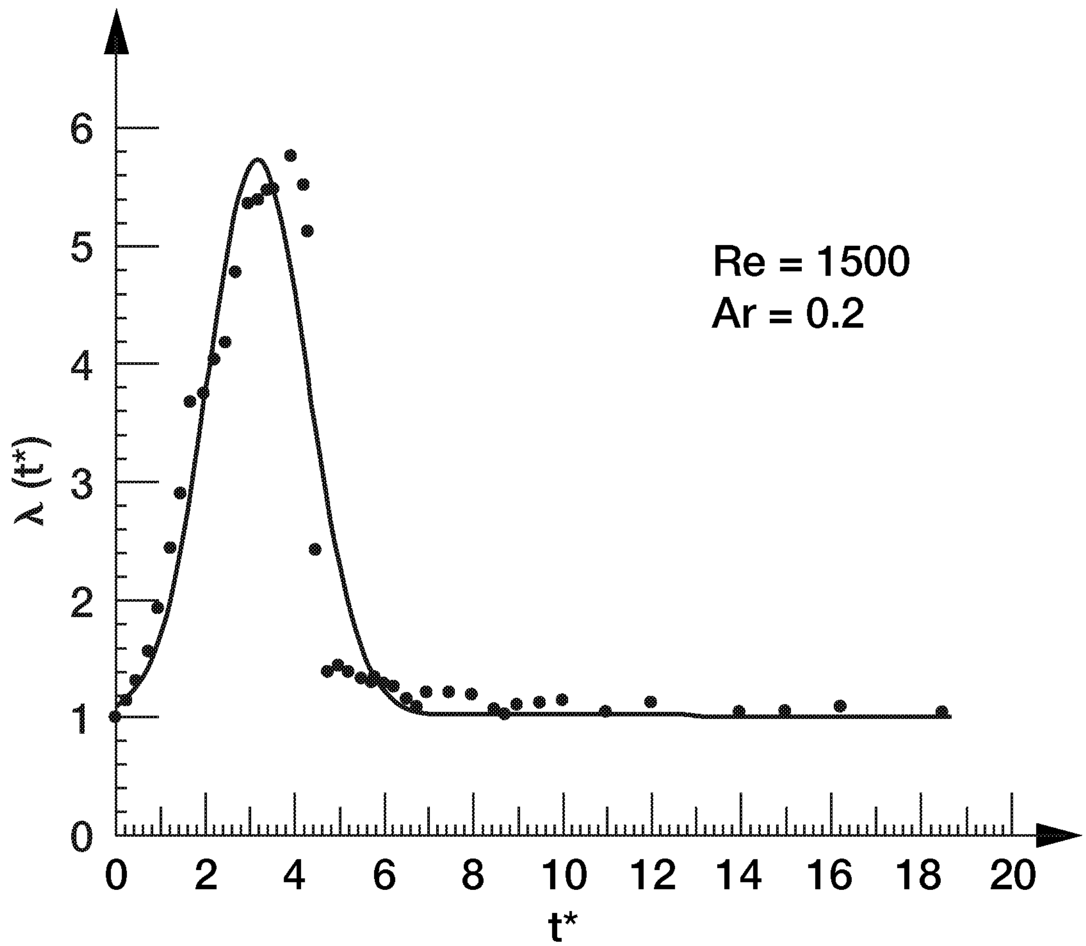


Magnitude of Velocity
Particle Imaging Velocimetry Measurements
$Gr = 3.18 \times 10^6$, Re = 1500, Ar = 0.2



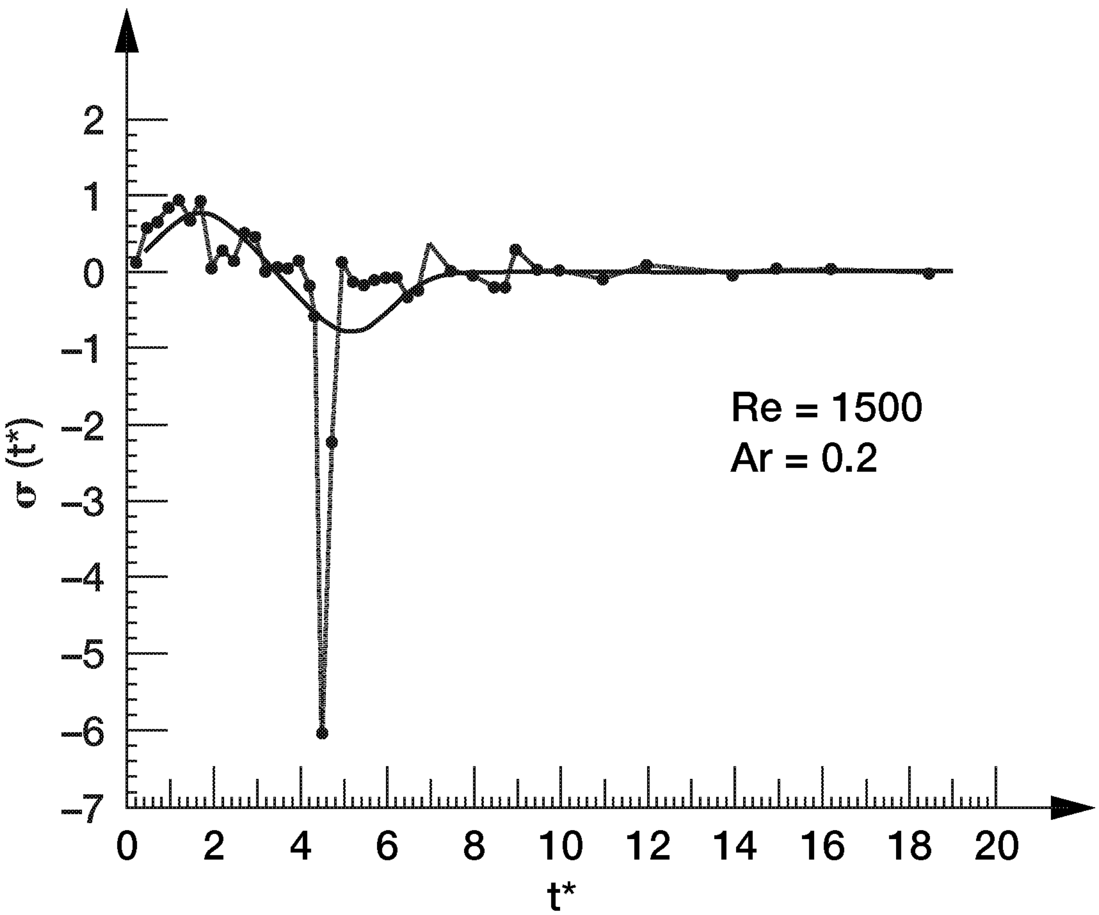
Gaussian Approximation of Length Stretch Ratio

Gr = 3.18×10^6



Time History of Liapunov Exponent

$Gr = 3.18 \times 10^6$



Horseshoe Map of Interface Folding

Gr = 3.18×10^6, Re = 3500, Ar = 0.2, t = 7.5 sec