IWPCTM12
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Recent Advances and Future Opportunities for Experiments to Investigate Rayleigh-Taylor Driven Mixing

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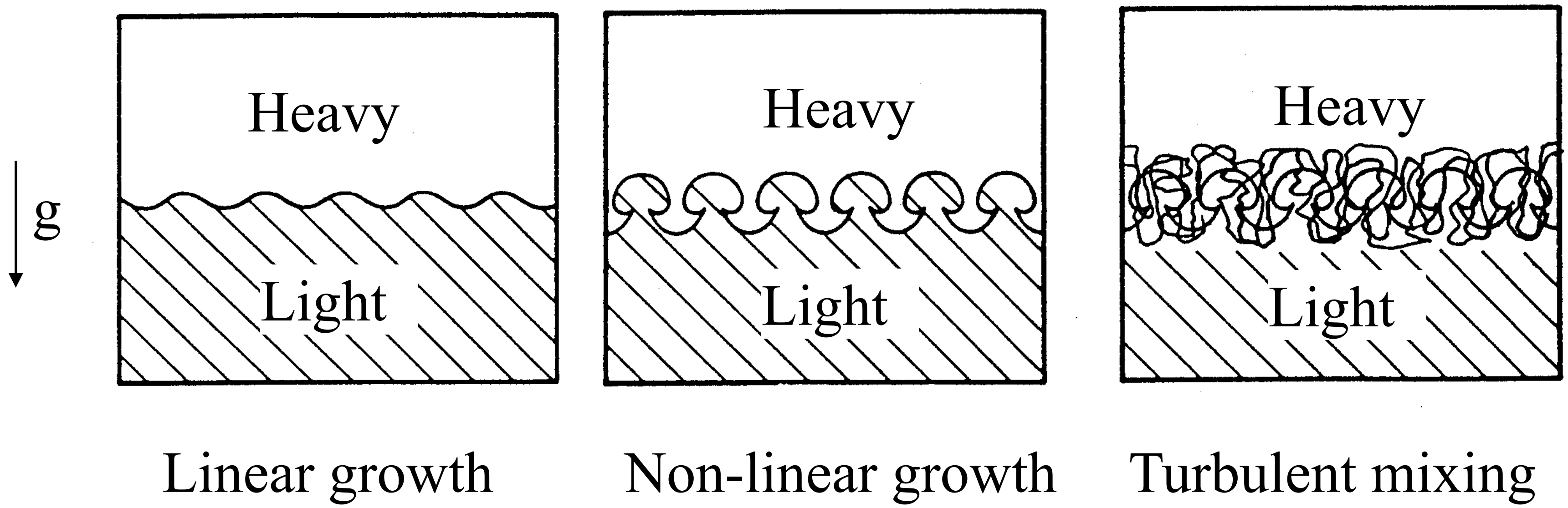
Tuesday, 13, July, 2010
LA-UR-10-04537

Rayleigh-Taylor (RT)



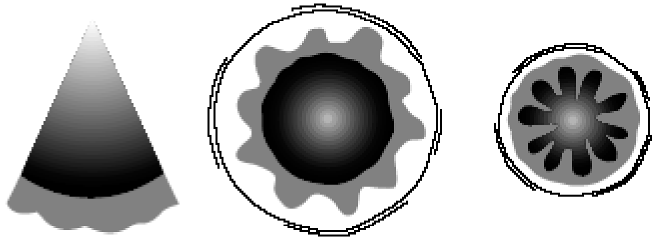
Main non-dimensional number: Atwood: $At \equiv (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$

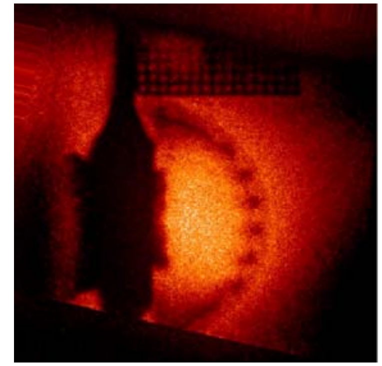
Interface is unstable if: $\nabla p \bullet \nabla \rho < 0$

Baroclinic generation of vorticity: $\frac{1}{\rho^2} \nabla p \times \nabla \rho$

Objective today is to discuss "small-scale", "high fidelity" RT experiments – my apologies for missing various contributions

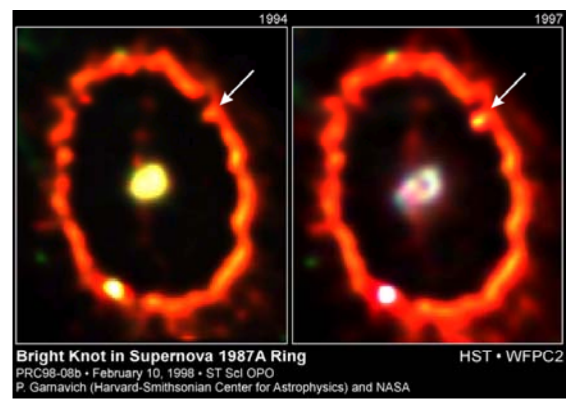
Applications





Technology:

- Degradation of ICF capsules (10^{-12}s).
- Formation of oil trapping salt domes (10^{15}s).
- Counter-gradient transport in engine cylinders with swirl.
- Modulation of heat transfer with twisted tapes in tubes.
- Atmospheric temperature inversions (clear air turbulence).
- Multi-phase mixing - drop disintegration.



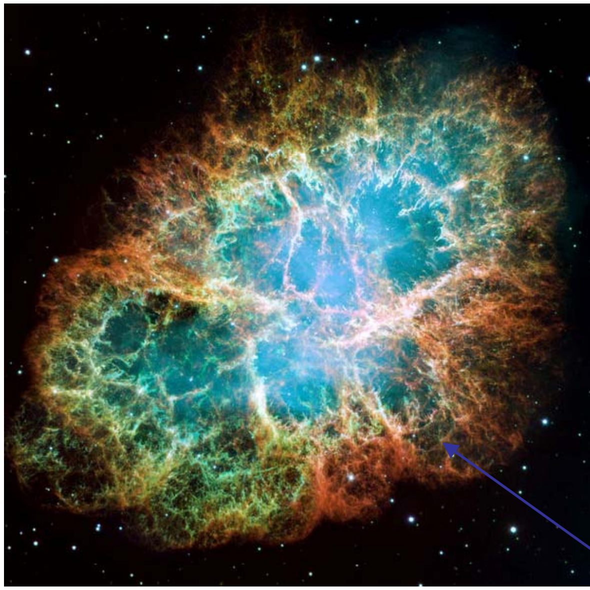
Bright Knot in Supernova 1987A Ring
PRC98-08b • February 10, 1998 • ST ScI OPO
P. Garnavich (Harvard-Smithsonian Center for Astrophysics) and NASA

Space:

- Super-Nova Remnants (SN1987A).
- g-Jitter - Bridgman crystal growth.

Applications

Rayleigh-Taylor instabilities affect many natural & man-made phenomena

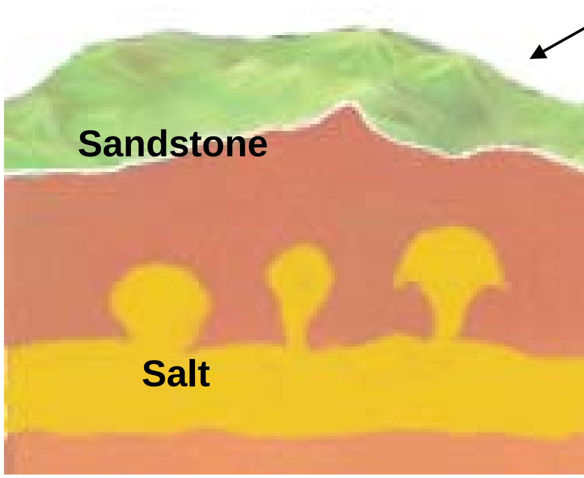


Supernova (10^{10} s)

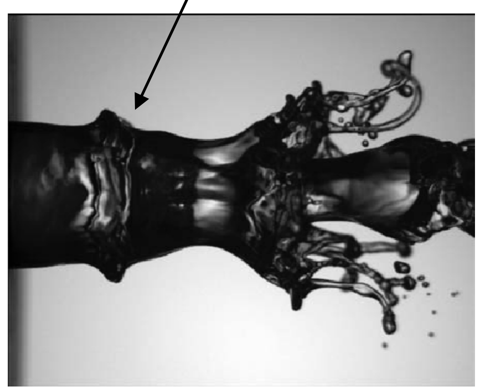
Eagle Nebula (10^{11} s)

Buoyancy-driven instabilities

Cirrus Coulds (10^{2} s)



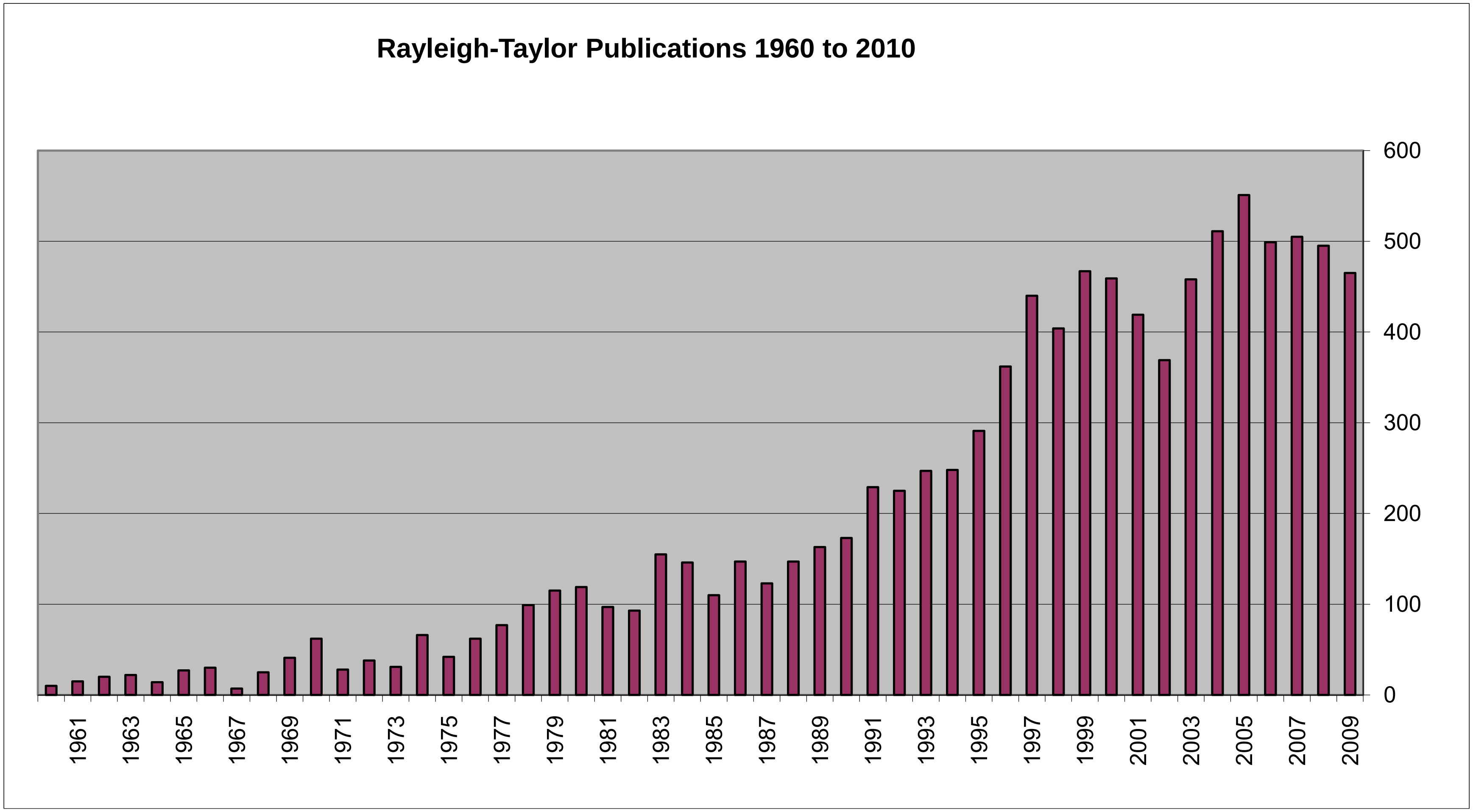
Salt domes (10^{15} s)



Droplets & Sprays (10^{-3} s)

Inertial Confinement Fusion (10^{-12} s)

RT Publications 1960-2010



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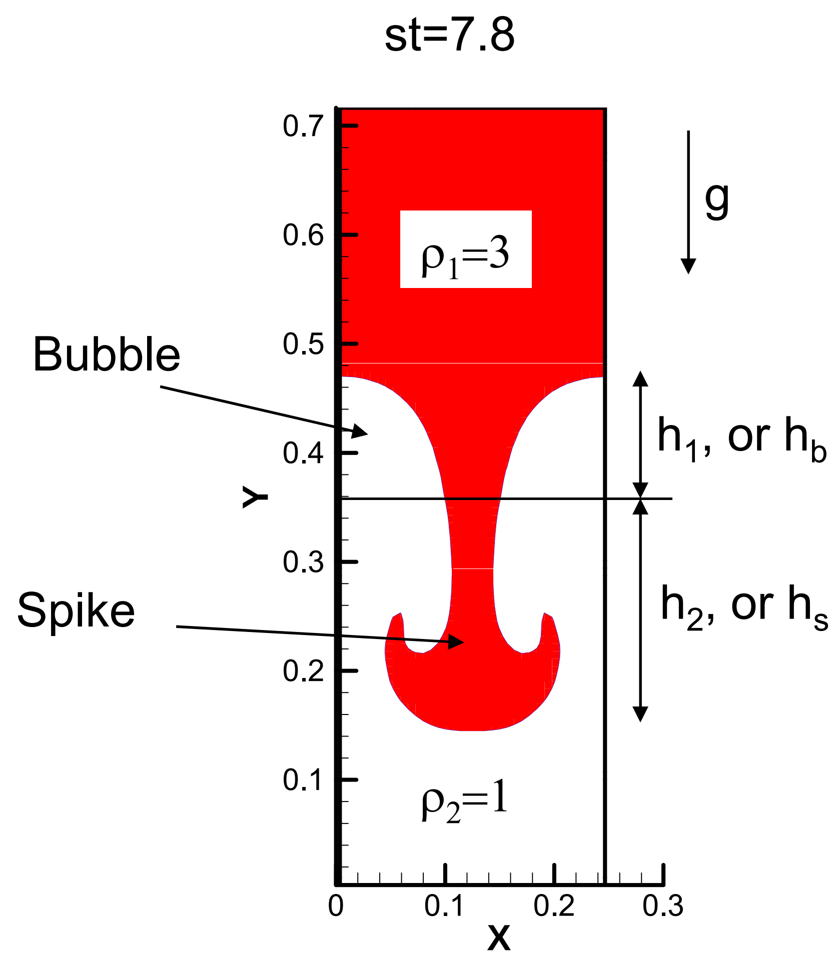
RT – definitions and notation

- The penetration of the bubble from the initial position of the interface is normally denoted "h_1" or "h_b".
- The penetration of the spike from the initial position of the interface is normally denoted "h_2" or "h_s".
- Only if A_t<0.1 is $h_1 \sim h_2$
- Asymmetry for large A_t is a characteristic RT and RM, KH also sees similar asymmetries.



Rayleigh-Taylor

- From Linear stability analysis the growth-rate of a small perturbation is given by:

$$A = A_0 e^{st},\ s = \pm\left\{kg\frac{(\rho_1 - \rho_2)}{(\rho_1 + \rho_2)}\right\}^{1/2} = \pm\{kgA_t\}^{1/2}$$

- The bubble "saturation" growth-rate is (Goncharov, 2002, & others):

$$V_{b,\infty}^{3D} = 1.02\sqrt{\frac{2A_t}{1+A_t}\frac{g}{k}}$$

- The late-time development (the bubble penetration height) of a RT turbulent mix is (Youngs, 1984, & others earlier):

$$h_1 = h_b = \alpha_b A_t g t^2$$

Consideration of RT mix experiments

- Very difficult
- The fluids
  - Miscible (brine/water, hot/cold, alcohols, gels)
  - Immiscible (kerosene/water)
- Physical parameters
  - Atwood number (small/large)
  - Surface tension
  - Viscosity (kinematic)
  - Refractive indices
  - Schmidt number
  - Strength

Consideration of RT mix experiments

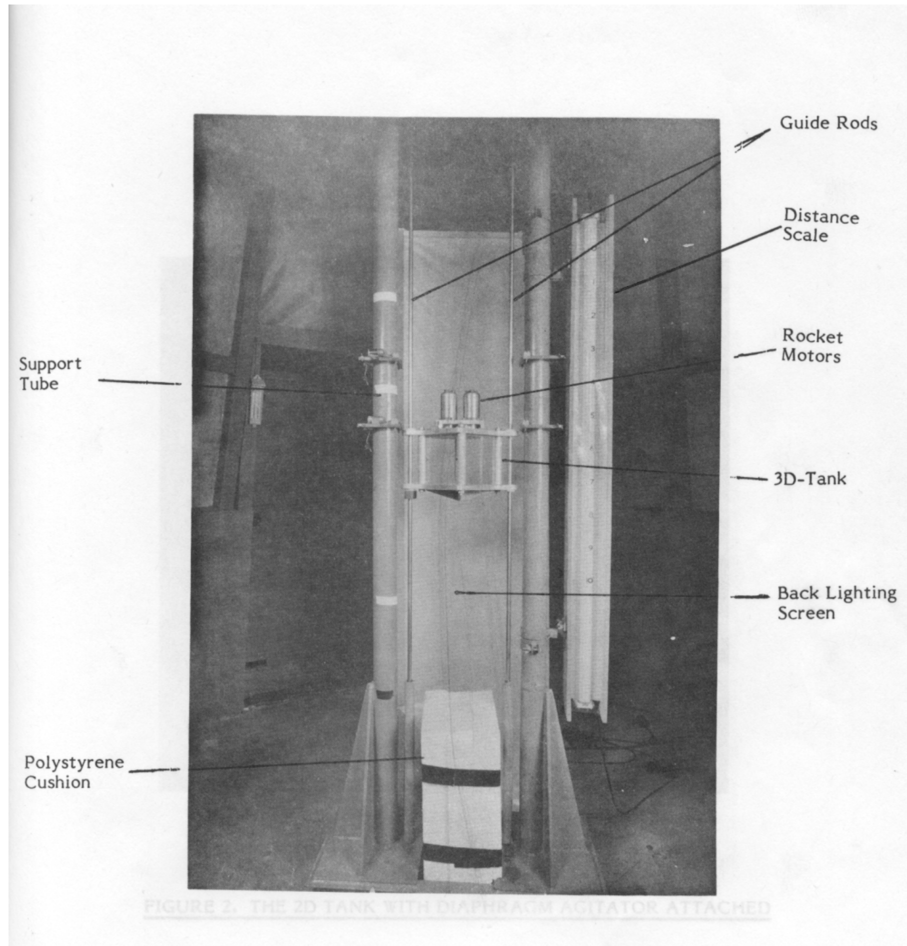
- Driving the mix
  - Gravity (set-up, and control of initial conditions)
  - Imposed acceleration (rubber tubing, weights, rockets, LEM, explosives)
- Safety
  - Fluids (SF_6, Mercury, flammable)
  - Equipment (speed, construction)
  - Diagnostics (electrical/water, lasers)
- Measurements
  - Transient (movies, PIV)
  - Probes (concentration, thermocouple, hot-wire/film)
- Time frame
  - Fast (20,000g!, transient)
  - Steady

Previous Experiments

Ken Read (1984)

The “Rocket Rig”

Aldermaston, UK.



Previous Experiments cont.

Rocket rig

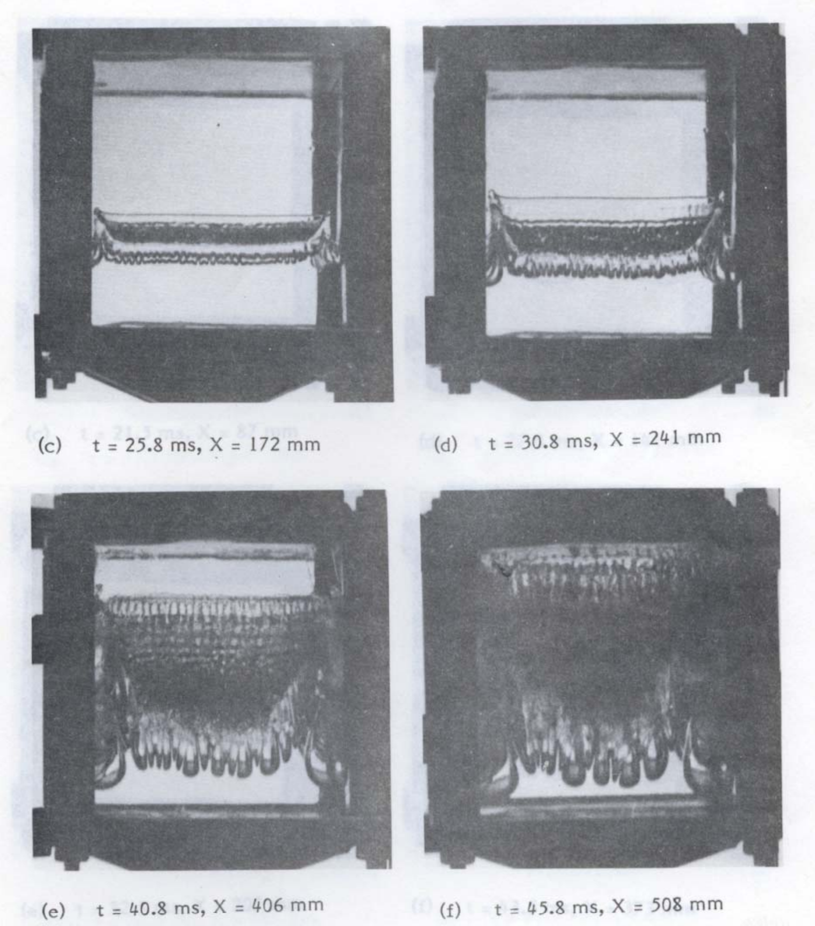


FIGURE 10. EXPERIMENT 29, ALCOHOL/AIR, 3D TANK, NO IMPOSED PERTURBATIONS

Photographs used to measure:

h_b and α

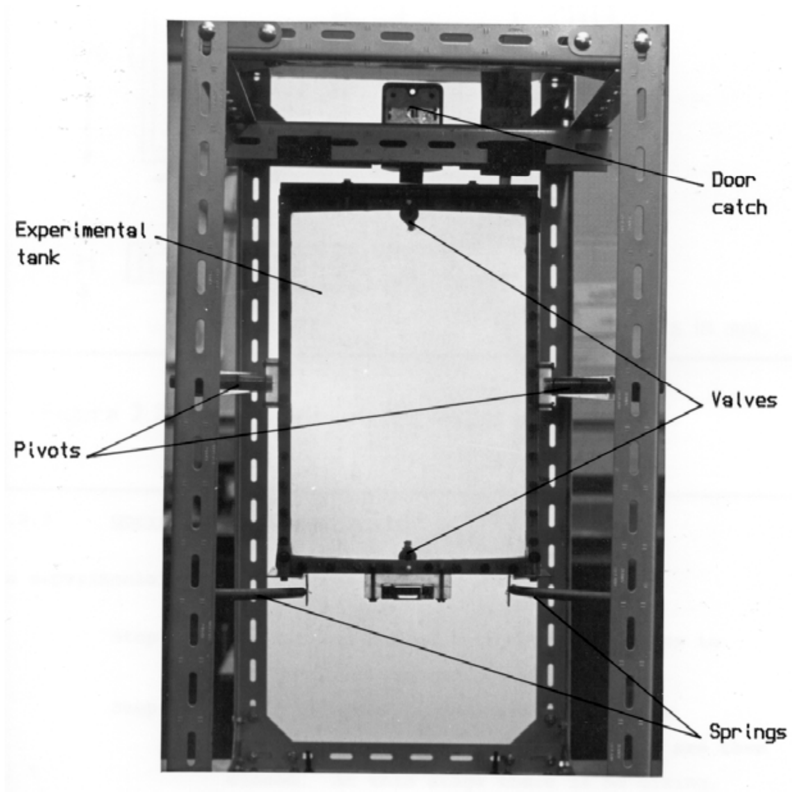
Previous Experiments cont.

Andrews, PhD (1986).

The "2-D Turning Tank".

Imperial College, UK.

Tank size: 25cm x 36cm x 0.5cm



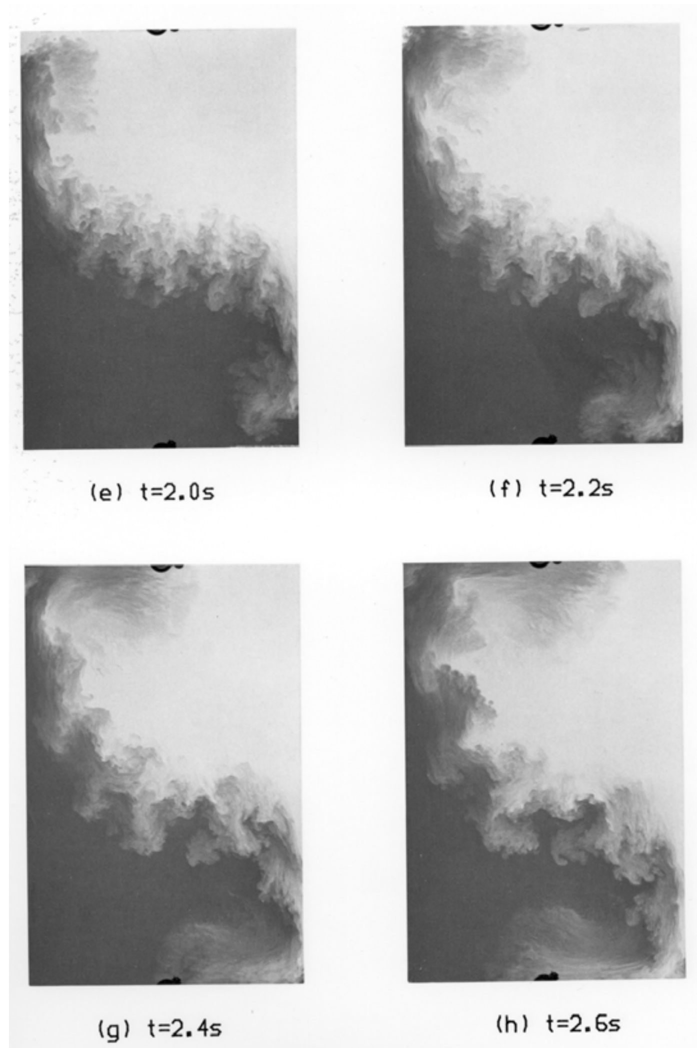
Previous Experiments cont.

2-D Turning Tank - Tilted-rig

Tilt angle = 55'

ρ_1=1.1 g/cm^3 (brine)

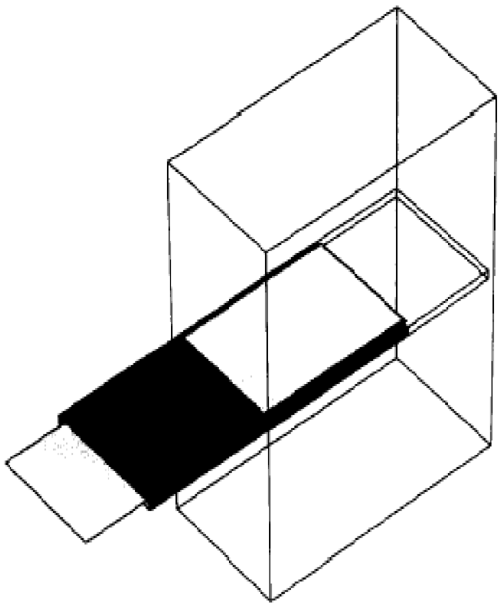
ρ_2=1.0 g/cm^3 (water)

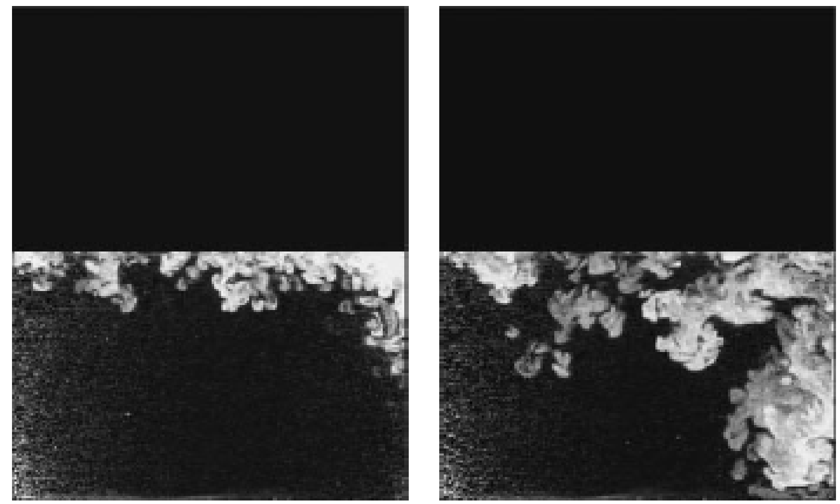


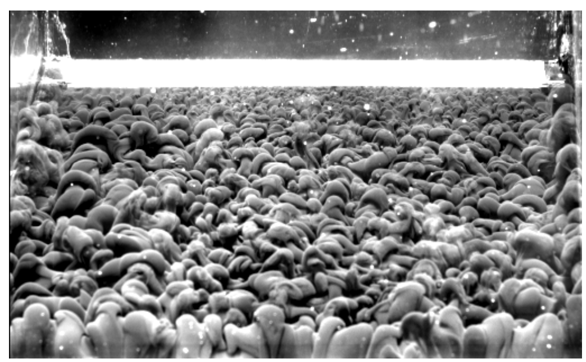
Densitometer analysis used to measure:

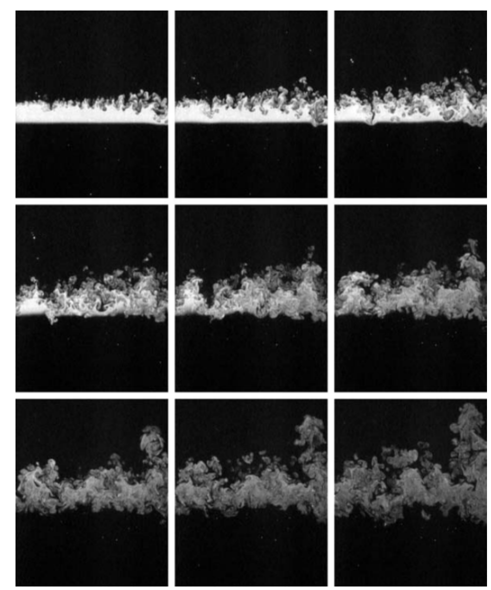
h_b, α, and mean density

Cambridge sliding plate (Dalziel et al., 1993 - onwards)





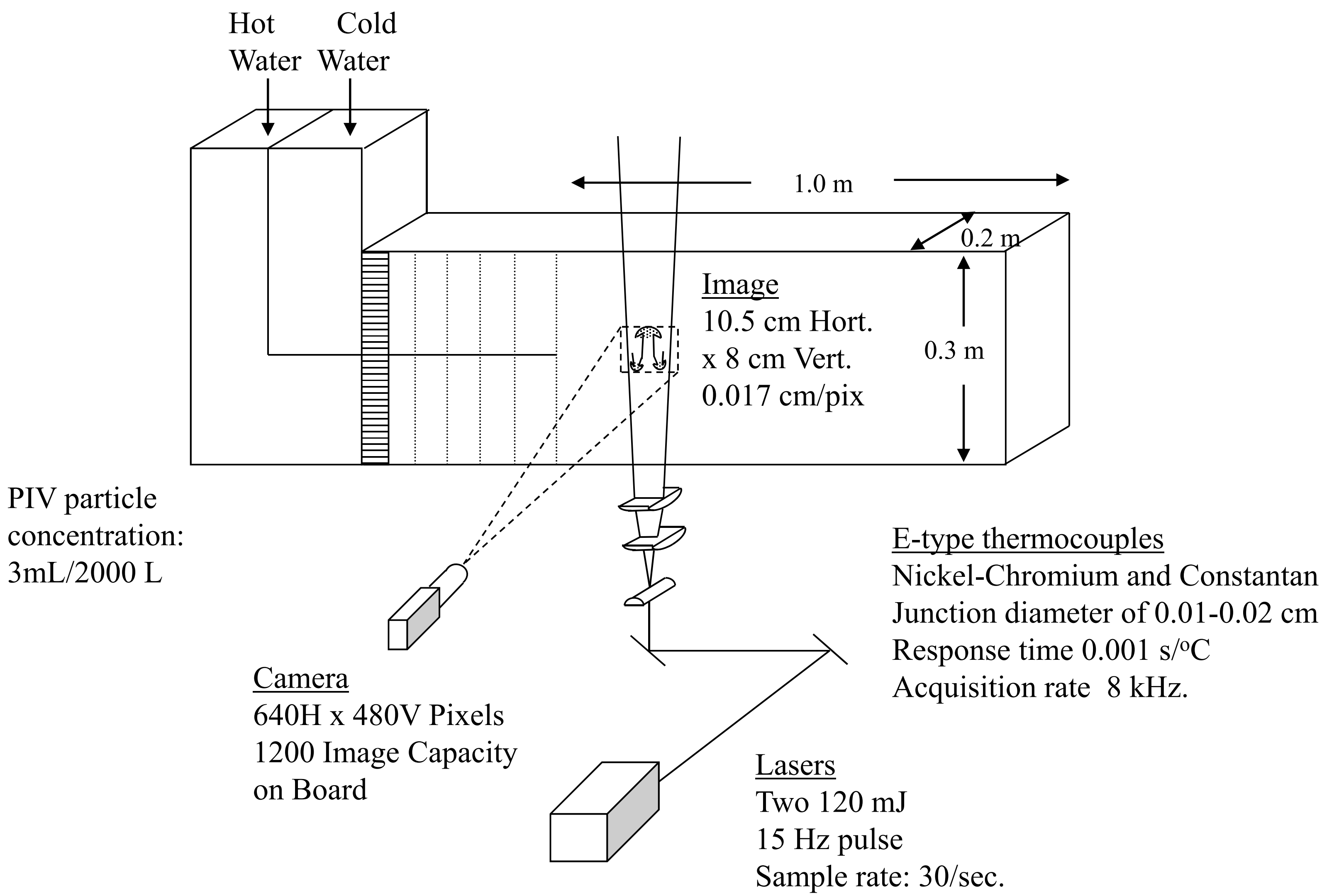




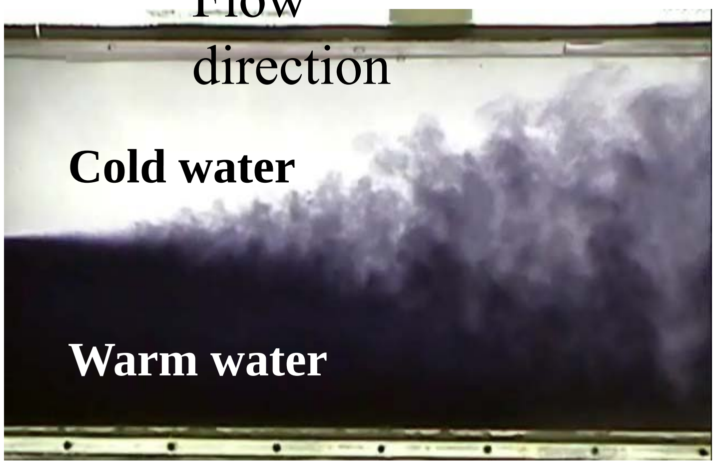
2 and 3 fluid measurements using:

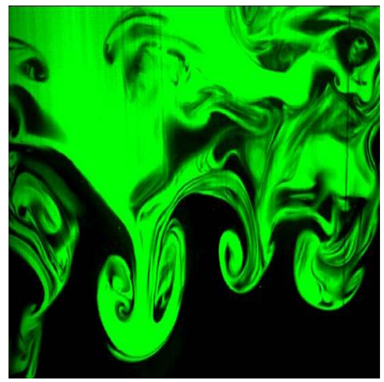
Conductivity probes, planar laser induced fluorescence (PLIF)

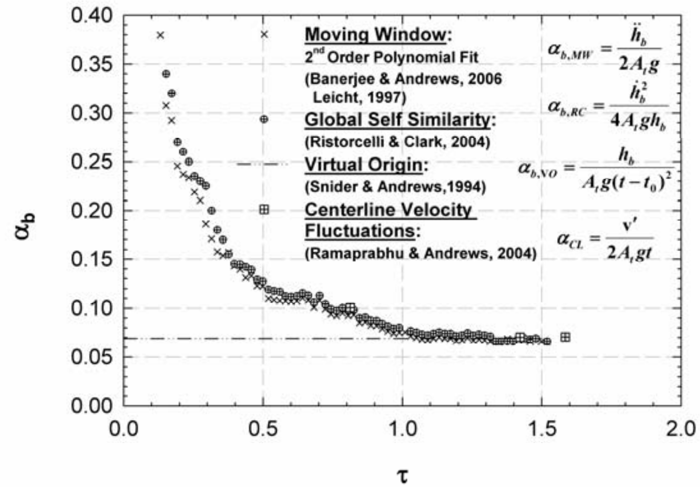
Texas A&M Water Channel



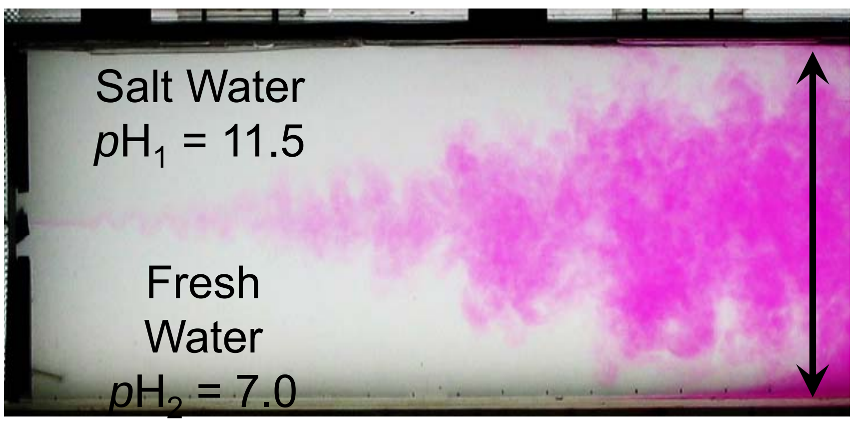
Water Channel Data 1996-2008



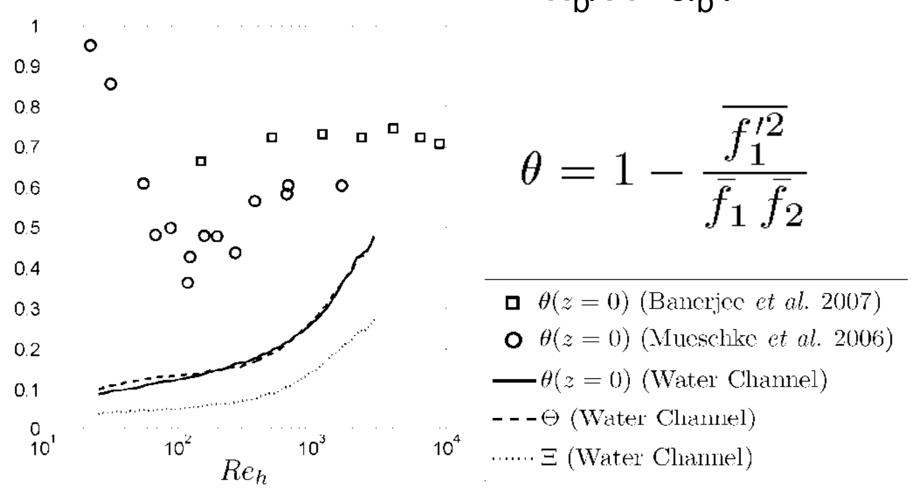




$h_b/H=\alpha_b\tau^2$



U_m = 5 cm/s



$$\theta = 1 - \frac{\overline{f_1'^2}}{\overline{f_1}\,\overline{f_2}}$$

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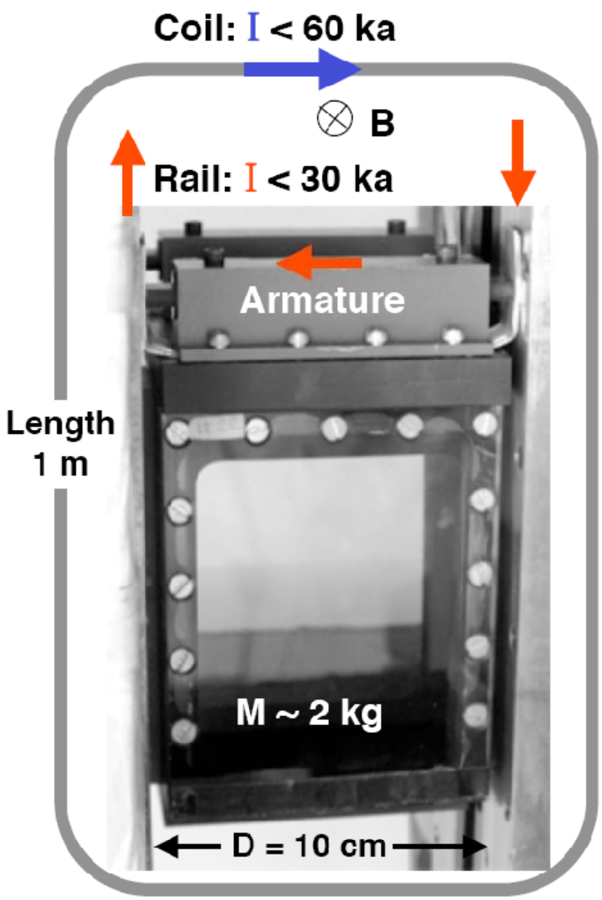
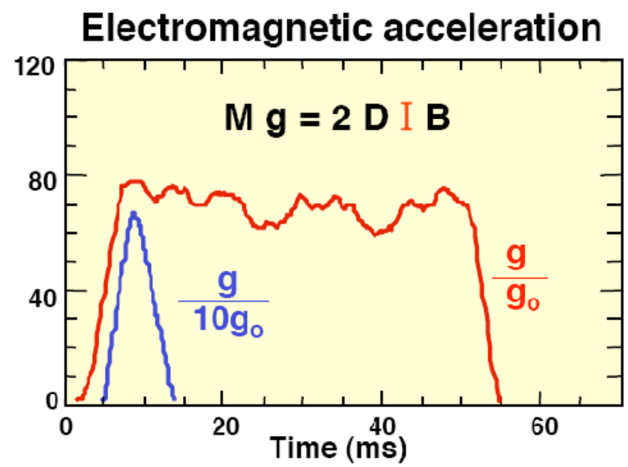
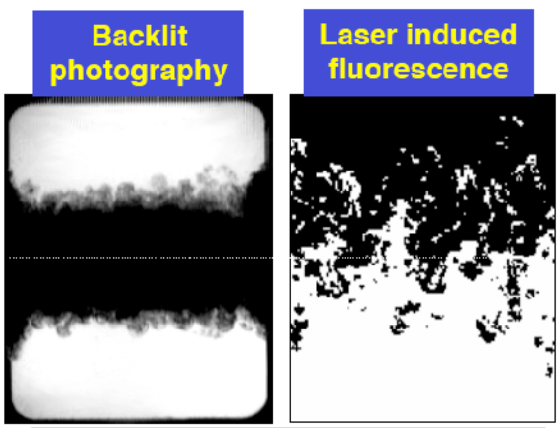
The LEM (Dimonte et al, PRE, 54, 3740, 1996)







PRL 80, 1212 & 3507 (1998)

Waddell et al., 2001 (with Jacobs)

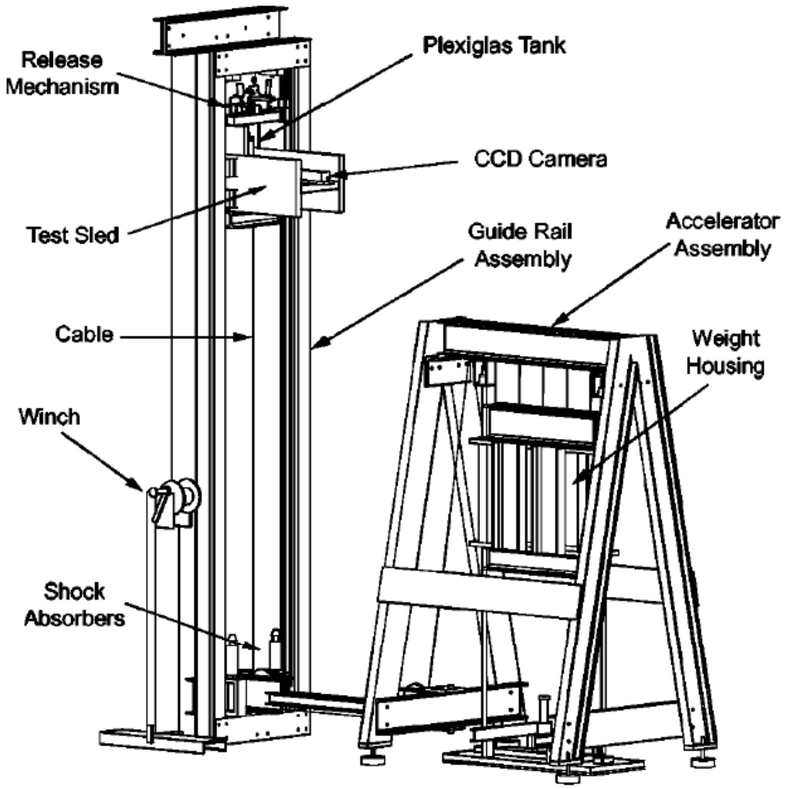


FIG. 1. Drawing of the experimental apparatus.

Phys. Fluids, Vol. 13, No. 5, May 2001 Experimental study of Rayleigh–Taylor instability 1267

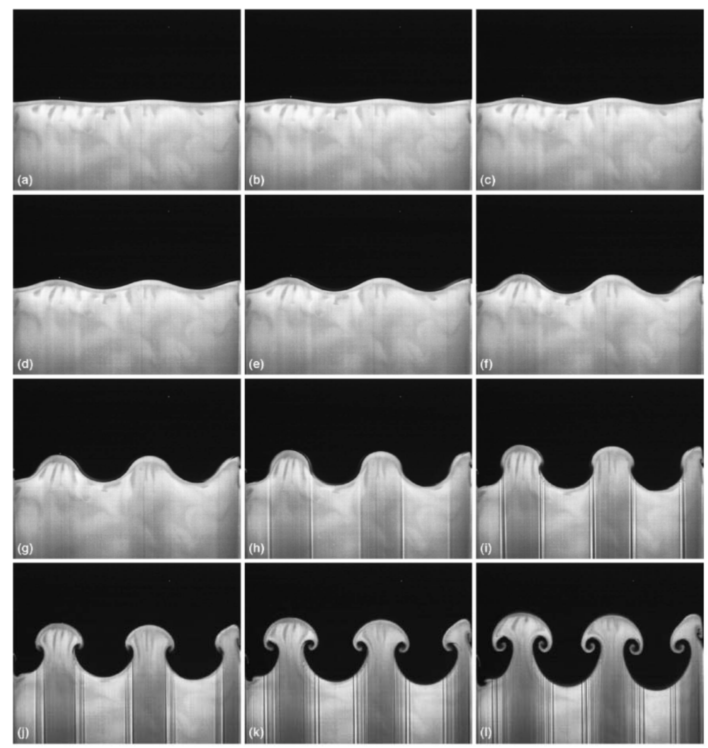
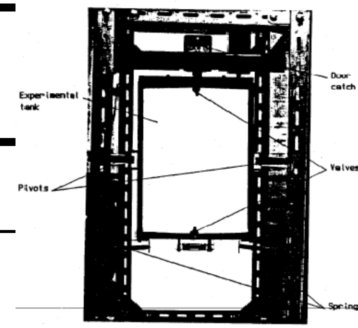
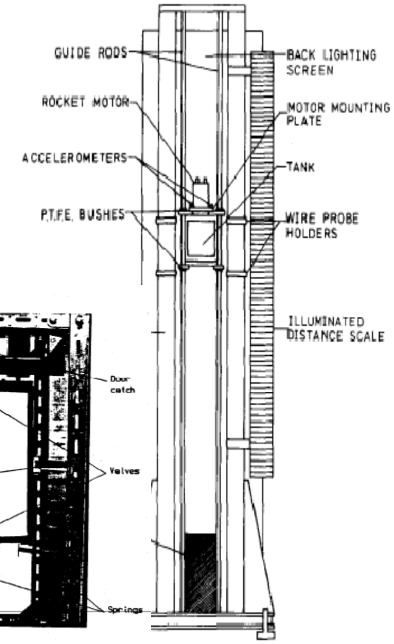


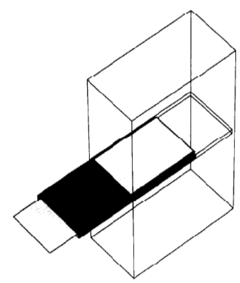
FIG. 4. A sequence of PLIF images showing the development of a miscible system with A=0.155 accelerated at 0.74 g with an initial perturbation wavelength of 54 mm. The first frame (a) was taken immediately after the test sled was released and there is a 0.033 s increment between each subsequent image.

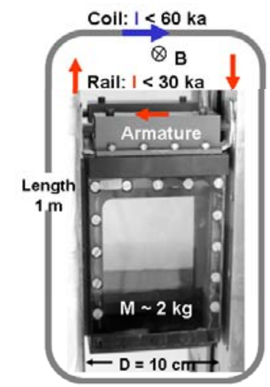
60 Years of RT Experiments

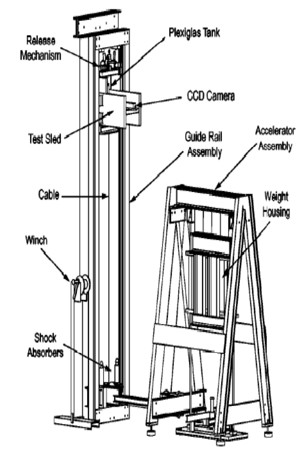
Experiments	Mechanism	A_t # (Run time)	Diagnostics
Lewis (1950) , Other experiments (1950-1979)	Various (**1- 100 g_0**)	**0.11 - 0.99** (**~ 10^{-3} s**)	**Imaging**
Read (1984)	Rockets (**25 -75 g_0**)	**0.231-0.997** (**< 10^{-2} s**)	**Imaging**
Andrews and Spalding (1986, 1990)	Inverting Stable Mix (**g_0**)	**0.048** (**~2s**)	**Imaging**
Jacobs *et. al.* (*1985-2005*)	Compressed Air, Drop Tank (**5 -10 g_0**)	**0.99** (**< 1 s**)	**Imaging**
Linden & Redondo (1993), Dalziel et. al (1993-present)	Fast Sliding Plate (**g_0**)	**0.0007-0.002** (**~5s**)	**Imaging, LIF, Conductivity measurements***
Dimonte & Schneider (*1996-2004*)	Linear Electric Motor (**20 -1000 g_0**)	**0.15-0.96** (**< 0.1 s**)	**Imaging, LIF**
Kucherenko *et. al.* (1997-2003)	Drop Tank (**650 g_0**)	**0.23-0.5** (**< 0.1 s**)	**Imaging**











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Some Experimental Reynolds Numbers

Experiment	Fluids	Atwood	h_{max} (m)	g/g_0	ν_{mix} (m^2/s)	Re_{max} (a)	Pr	η_k (m)	η_b (m)
Read	Water/Pentane	0.231	0.06	50.00	1.23E-06	146682	7	8.01E-06	3.03E-06
LEM	Decane/Water	0.16	0.04	500.00	1.00E-06	297366	7	3.46E-06	1.31E-06
Water Channel	Cold Water /Hot Water	0.001	0.15	1.00	1.00E-06	6631	7	2.04E-04	7.72E-05
Gas Channel (TAMU)	Air/Helium	0.75	0.60	1.00	2.82E-05	51552	0.7	1.75E-04	2.10E-04
Cambridge Exp (Dalziel)	Brine/Water	0.05	0.25	1.00	9.54E-07	105935	700	4.26E-05	1.61E-06

$$\mathrm{Re}^a = \sqrt{\frac{gA_t}{6}}\frac{(2h_1)^{3/2}}{\upsilon}$$

RT Brief Literature Survey to 2006

(Andrews & Banerjee)

Year	Authors	Fluids	Atwood #	Mode	2D-3D	Diagnostics	Run time	Reference
1950	Lewis 20 g_0	A/B, A/G & A/W	0.99	S	2D	Imaging	~ 10^{-2} s	•Proc. R. Soc. Lon A, 202, pp. 81-96 (1950)
1954	Allred *et. al.* 20-100 g_0	W/nH, W/OA, W/I, nH/A	0.188-0.995	S	2D	Imaging	~ 10^{-2} s	•LANL Report LA-1600 (1954)
1960	Emmons *et. al.* 2.5 g_0	CT/A & M/A	0.107-0.997	S	2D	Imaging	< 0.1 s	•J. Fluid Mech. 7, pp. 177-193 (1960)
1962	Duff *et. al.*	(Ar+Bm)/A, (Ar+Bm)/H	~ 0.9	S	2D	Imaging	< 0.2 s	•Phy. Fl. 5, 417-425
1973	Ratafia < g_0	OA/W	0.095	S	2D	Imaging	< 1 s	•Phy. Fl. 16, pp.1207-1210 (1973)
1973	Cole & Tankin (15g_0)	A/W	0.99	S	2D	Imaging	< 10^{-2} s	•Phy. Fl. 16, pp.1810-1820 (1973)
1979	Popil &Curzon (h_m ~ 9 cm) 3.5 g_0	A/W	0.99	S + M	2D	Imaging	< 0.3 s	•Rev. Sci. Instr., 50, pp. 1291-129 (1979)
1984	Read (h_m ~ 5- 6 cm) 25 -75 g_0	W/P, SI/P, EA/A	0.231-0.997	M	2D/3D	Imaging	< 10^{-2} s	•Physica D, 12, pp. 45-58 (1984)
1985 – 2001	Jacobs *et. al.* (h_m ~ 5 – 9cm) 5 -10 g_0	A/W	0.99	S+M	3D	Imaging	< 1 s	•J. Fluid Eng. 107, 460-466 (1985) •J. Fluid Mech. 187, 353-371 (1988) •Phy. Fl. 13, pp. 1263-1273 (2001)

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Year	Authors	Fluids	Atwood #	Mode	2D-3D	Diagnostics	Run time	Reference
1990	Andrews & Spalding (g_0)	Br/W	0.048	M	2D	Imaging	~ 2 s	•Phy. Fl. A, 2, pp.922-927 (1990)
1991, 1994	Linden & Redondo (h_m ~ 25 cm) (g_0)	Br/W	10^{-4} to 0.05	M	3D	Imaging, LIF, Conductivity measurements	~ 3-4 s	•Phys. Fl. A, 3, pp.1269-1277 (1991) •J. Fluid Mech. 265, 97-124 (1994)
1993, 1999	Dalziel et. al. (h_m ~ 25 cm) (g_0)	Br/(W + P2)	2×10^{-3} to 7×10^{-4}	M	3D	LIF	~5s	•Dyn. Atmos. Oceans, 20, 127-153 (1993) •J. Fluid Mech., 399, pp. 1-48 (1999)
1994-2004	Andrews, Snider, Wilson, Ramaprabhu, Kraft & Mueschke (h_m ~ 15 cm) (g_0)	HW/CW	10^{-4} to 10^{-3}	M	3D	Imaging, Thermo-couples, PIV and PLIF	~ 600 s	•Phys. Fl., 6, 10, pp.3324-3334 (1994) •Phys. Fl. A , 11,pp. 2425-2433 (1999) •Phys. Fl. A, 14, pp. 938-945 (2002) •J. Fluid Mech., 502,pp. 233-271 (2004)
1990-1996	Meshkov et al.	Jelly	~1	M	Cylindrical	Imaging	~1 ms	•Proceedings IWPCTM3,4 & 5

http://www.iwpctm.org/

Year	Authors	Fluids	Atwood #	Mode	2D-3D	Diagnostics	Run time	Reference
1996-2004	Dimonte & Schneider ($h_m \sim 4.4$ cm) 20 - 1000 g_0	W/F, D/W, D/Br, Br/F, Hx/Br, H/W, D/Br, W/LM, BT/LM, F/LM, S/H, S/BT, S/F, S/D	0.15 - 0.96	M	3D	LIF & Imaging	< 0.1 s	•Phys. Rev. E, 54, 3740-3743 (1996) •Phys. Rev. E, 80, 1212-1215 (1998) •Phys. Plasmas, 7, 2255-2269 (2000) •Phy. Fl., 12, pp.304-321 (2000) •Phys. Rev. E, 69, 1-14 (2004)
1997 - 2003	Kucherenko *et. al.* ($h_m \sim 6$ cm) 650 g_0	G/B, W/Hg, W/Kl, B/(W+G)/SHS	0.23 - 0.5	M	3D	Pulsed x-ray photography	< 10^{-2} s	•LPB, 15,pp. 25-31 (1997) •LPB, 21, pp. 369-373 (2003) •LPB, 21, pp. 375-379 (2003)
2004 - 2006	Andrews & Banerjee ($h_m \sim 40$ cm) (g_0)	A/H	0.035-0.755	M	3D	Hot wire, Imaging	~ 300 s	•Phys. Fluids 18-3, pp. 035107 (2006) •JFM, In Press, 2010

Index for Fluids:

A: Air, Al: Alcohol, Ar: Argon, B: Benzene, Br: Brine, BT: Butane, Bm: Bromine, CT: Carbon Tetrachloride, D: Decane, EA: Ethyl Alcohol, F: Freon, G: Glycerin, H: Helium, Hg: Mercury, Hx: Hexane, I: Iso-Amyl Alcohol, KI: Klerichi liquid (Formic-Malonic Acid Talium), LM: Liquid Metal , M: Methanol, nH: n-Heptane; OA: Octyl Alcohol, P: Pentane, P2: Propan-2-ol, PT: Petrol; S: SF6, SI: Sodium Iodide, SHS: Sodium Hyposulfite, W: Water, HW: Hot Water, CW: Cold Water.

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Various α associated with $h_b = \alpha A_t g t^2$ at small At

Straight line intercept: Read (1984)

$$\alpha_{grad} = \frac{d(h_b)}{d(A_t g t^2)}$$

Virtual origin: Snider & Andrews (1994)

$$\alpha_{VO} = \frac{d(h_b)}{d(A_t g (t - t_0{}^2))}$$

Moving window quadratic fit: Leicht (1997)

$$\alpha_{MW} = \frac{\ddot{h}_b}{2A_t g}$$

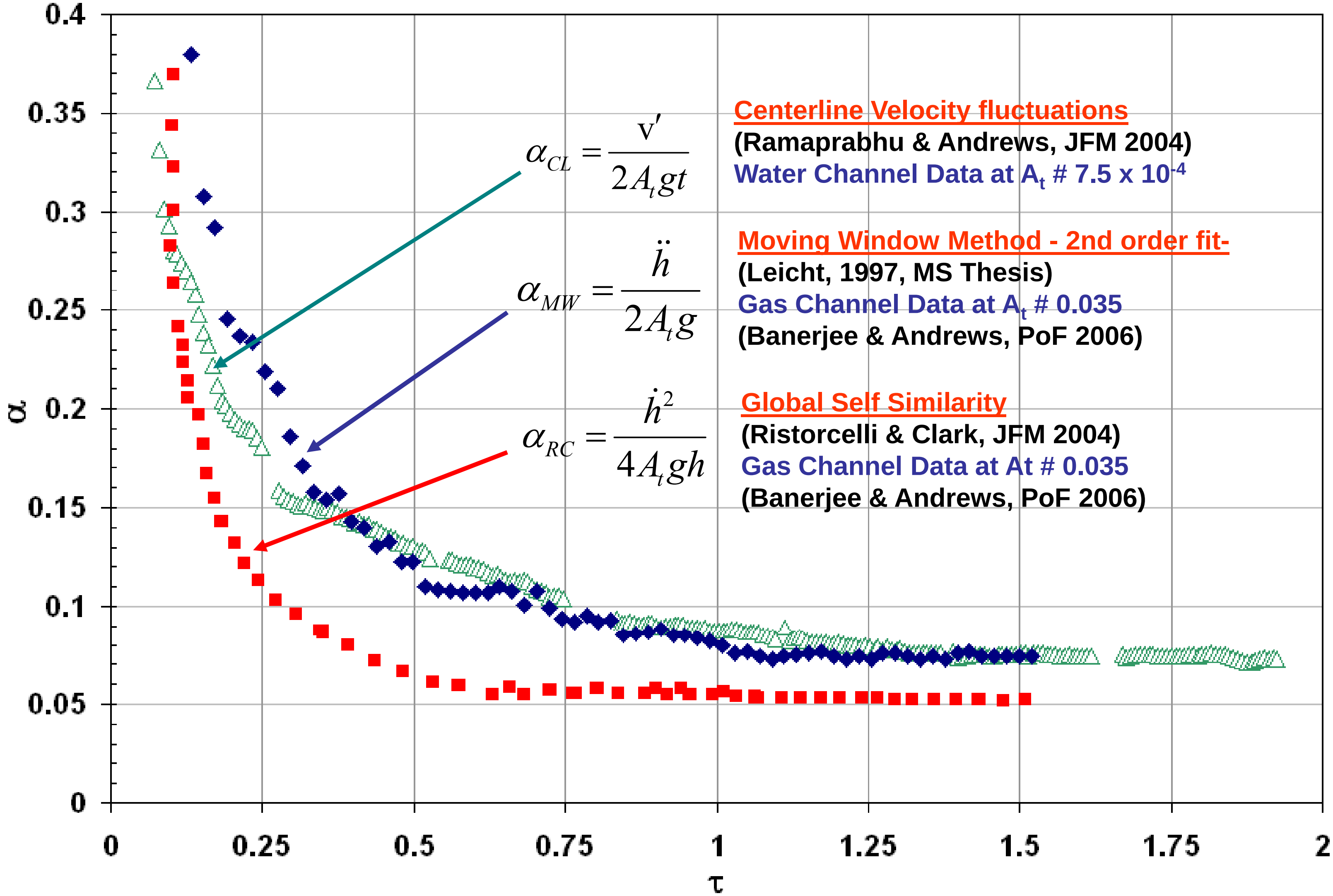
Centerline velocity: Ramaprabhu (2004)

$$\alpha_{CL} = \frac{v'}{2A_t g t}$$

Global self-similarity: Ristorcelli & Clark (2004)

$$\alpha_{RC} = \frac{\dot{h}_b{}^2}{4A_t g h}$$

More ways to measure α



α – effect of initial conditions

- Recent work (Dimonte et al., 2004 – the α-group paper) suggests quite different values for mode coupling vs. growth directly from initial conditions:

Influence of initial perturbations on turbulent Rayleigh–Taylor instability 21

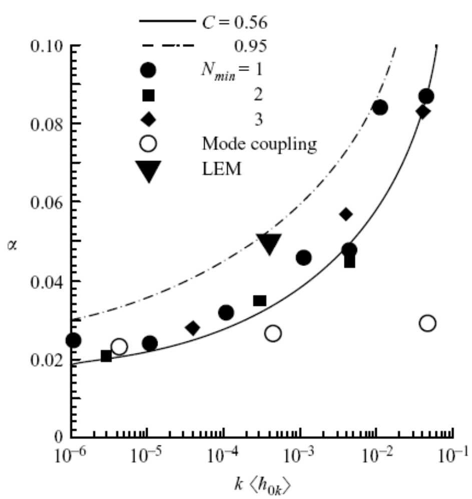
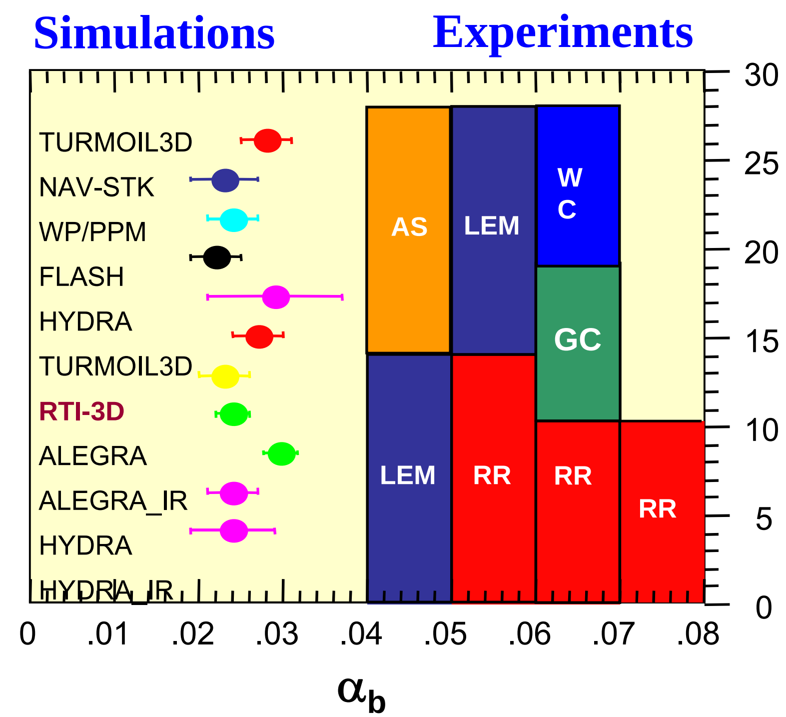


FIGURE 14. Comparison of α_b from the model and NS. Open circles show insensitivity of the mode-coupling cases to the initial amplitudes.



Comparison of α_b from codes and expts: LEM is the Linear Electric Motor, RR is rocket rig, K is Kucherenko, AS is Andrews Spalding, WC & GC are the TAMU water & gas channels

- From Dimonte et al. (2005): *k* based on the dominant wavelength in the distribution, and h_0 the RMS initial amplitude. *Very* small A_0/L ~ 10-4 needed for mode coupling.

RTI + surface tension or viscosity

- Surface tension adds a pressure jump $\gamma\left(R_1^{-1} + R_2^{-1}\right)$

$$s = \pm\left\{\frac{k^2}{(\rho_1+\rho_2)}\left[\frac{g(\rho_1-\rho_2)}{k} - k\gamma\right]\right\}^{1/2}$$

- The "cut-off" wavelength is: $\lambda_c = \frac{2\pi}{k} = 2\pi\left\{\frac{\gamma}{g(\rho_1-\rho_2)}\right\}^{1/2}$

- Different viscosities for the two fluids adds great complexity, however, for the simpler case of $\nu_1=\nu_2$, $\rho_1>\rho_2$ and $\gamma=0$ Chandrasekhar showed that the unstable arrangement is unstable for all wave numbers, but there exists a "most unstable" wavelength, approximated from Chandrasekhar by Youngs (1984) as:

$$\lambda_m \approx 4\pi\left\{\frac{\nu^2}{g}\frac{\rho_1+\rho_2}{\rho_1-\rho_2}\right\}^{1/3} \; and \; s_m = \left\{\frac{\pi g}{\lambda_m}\left(\frac{\rho_1-\rho_2}{\rho_1+\rho_2}\right)\right\}^{1/2}$$

RTI + an initial density gradient

Adding an initial density gradient $(\rho_1-\rho_2)/\Delta$ reduces the density contrast across the initial interface and might be expected to effect wavelengths that are O(Δ) or less. Using the analysis of LeLevier et al. (1955), Smeeton & Youngs (1987) gave the following formula (more recent work can be found in Livescu, 2005):

$$s=\left(\frac{2\pi g}{\lambda+\pi\Delta}\frac{\rho_1-\rho_2}{\rho_1+\rho_2}\right)^{1/2}=\left(k_{eff}\,g\frac{\rho_1-\rho_2}{\rho_1+\rho_2}\right)^{1/2}=\left(\frac{2\pi g}{\lambda/\Delta+\pi}\frac{(\rho_1-\rho_2)/\Delta}{\rho_1+\rho_2}\right)^{1/2}$$

As Δ→0 reduces to our previous formula. But as λ→0 the growth rate of wavelengths < O(Δ) tend to a constant that reduces as the initial interface gradient decreases. So they all tend to grow together at the same “slow” rate, causing an effective “delay” of about

$$t_{delay}\propto\left(\frac{\Delta}{2g}\frac{\rho_1+\rho_2}{\rho_1-\rho_2}\right)^{1/2}$$

RT Asymmetry Between Bubbles and Spikes

- The Bousinesq approximation for small density difference flows says that density differences can be neglected everywhere in the governing equations except the buoyancy term (this is not the Bousinesq concept of eddy viscosity for turbulence modeling!).

- Computational evidence suggests symmetry between bubbles and spikes up to ~ Atwood=0.5, and clear asymmetry for Atwood > 0.7
- Dimonte and Snider (2000) give:

$$\frac{\alpha_s}{\alpha_b} = \left(\frac{\rho_s}{\rho_b}\right)^{D_\alpha}$$

where $D_\alpha \sim 0.33 \pm 0.05$

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Unclassified

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More on RT "spikes"

- The spike formula Eq.11 (and its 3D equivalent) are poor for $A_t > 0.1$ (2-D) and $A_t > 0.3$ (3-D)

- The spike continues to accelerate, as shown by Goncharov (2002) & Ramaprabhu and Dimonte (2005):

- The reason for this continued acceleration is not clear, but a changing shape for the head of the spike, associated with the formation of KH, is the likely cause.

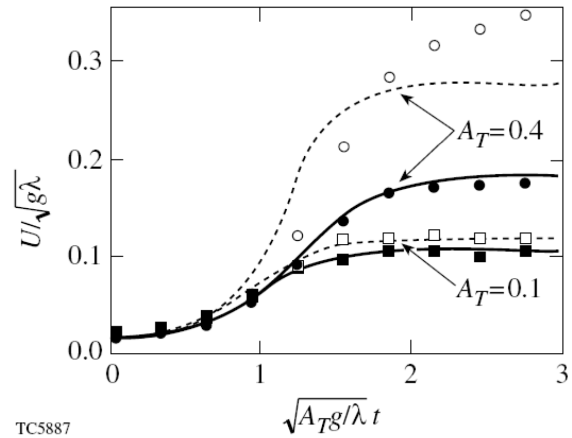
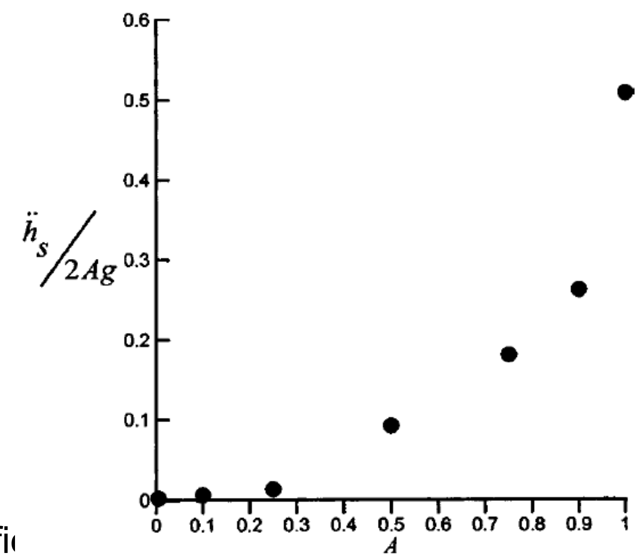


FIG. 3. Bubble (solid lines, solid circles, and squares) and spike (dashed lines, open circles, and squares) velocities calculated using the potential model (lines) and numerical simulation (circles and squares).

Goncharov



R & D

RT Measurements for Turbulence Model Development – Examples from TAMU

$$\rho^* = \frac{(\rho - \rho_{\min})}{(\rho_{\max} - \rho_{\min})} \qquad \overline{\rho^*} = \frac{\sum_1^n \rho_i^*}{n}$$

$$B_0 = \frac{n\sum_1^n \rho_i^{*2} - \left(\sum_1^n \rho_i^*\right)^2}{n(n-1)}$$

$$v' = v - \overline{v}$$

Molecular mix fraction

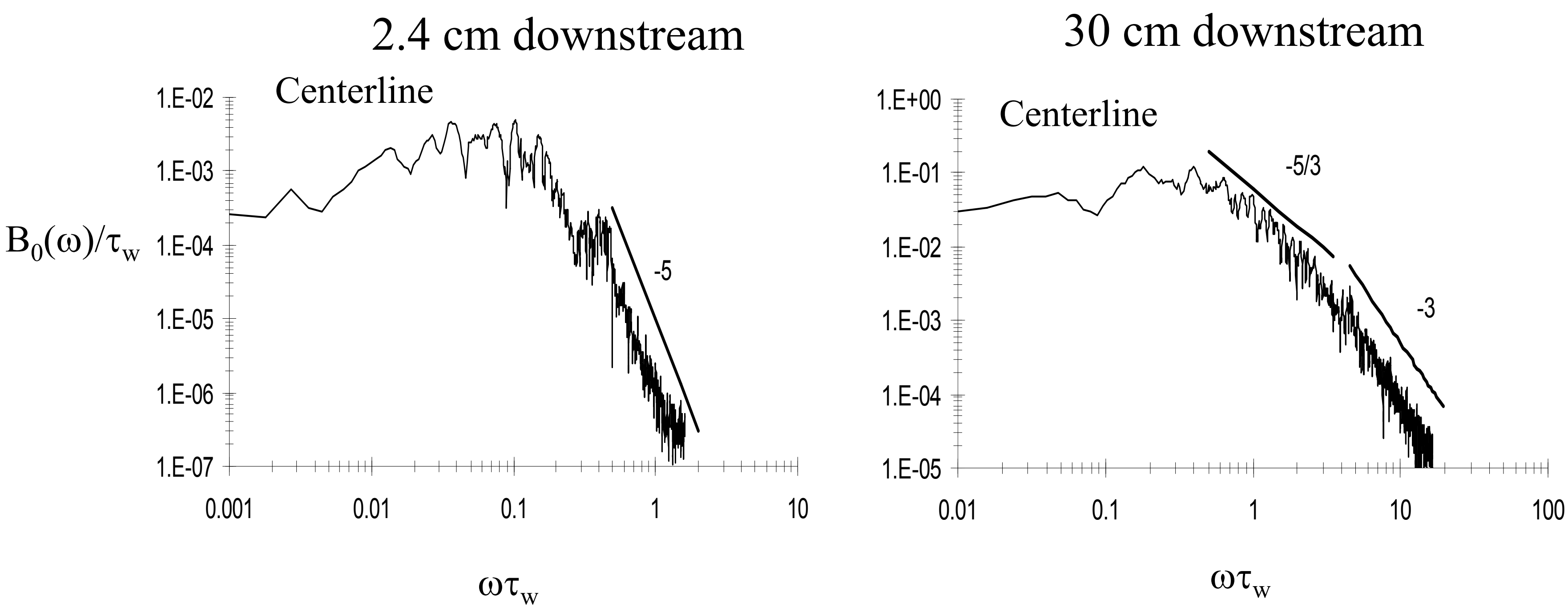
$$\theta \equiv 1 - B_0 / B_2$$

Turbulent mass flux (vertical direction)

$$m_z' = \overline{\rho' v'}$$

Density Fluctuation Power Spectra

TAMU Water Channel ~ 2002



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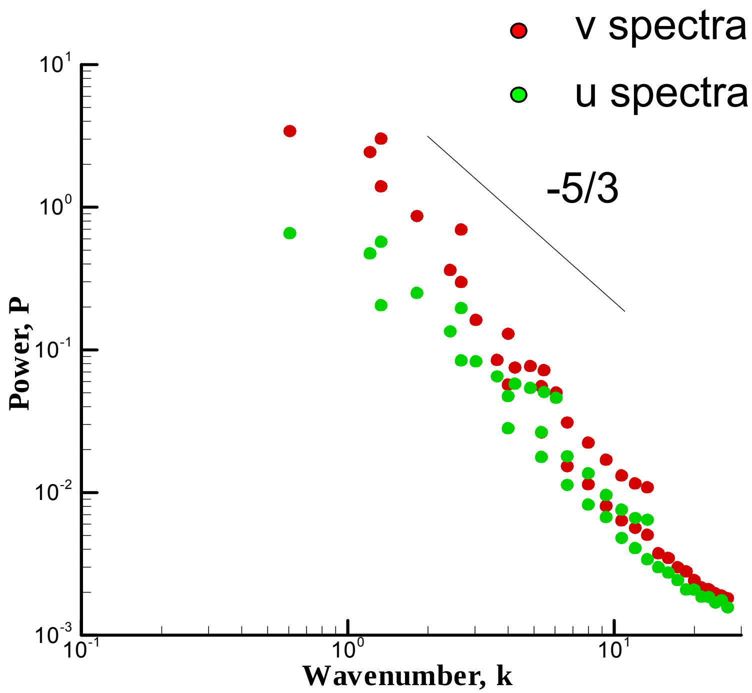
RT Mix Measures

- Wave number velocity spectra at the CL of the water channel (35 cm down stream):

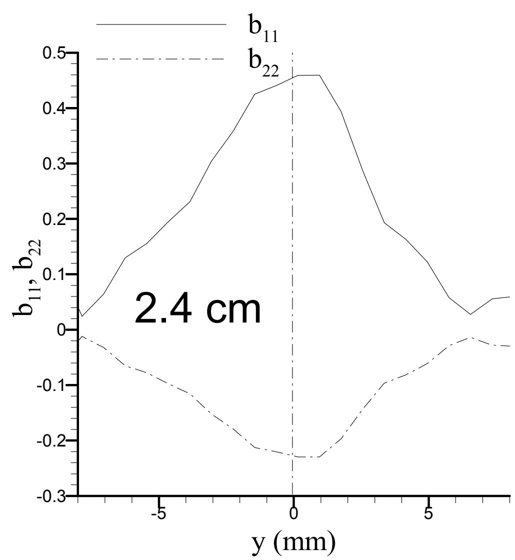


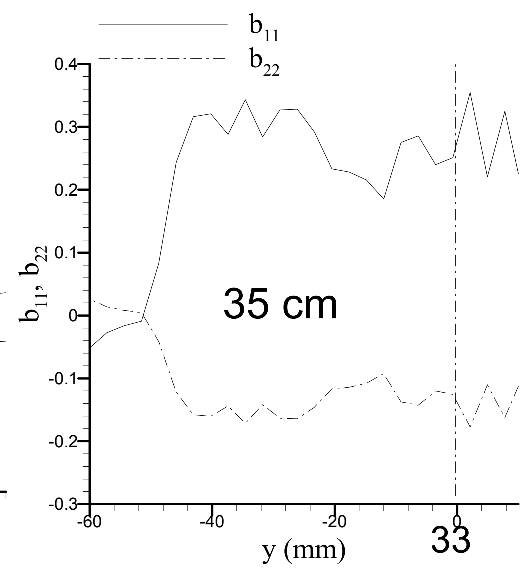
The anisotropy tensor

$$b_{ij} = \frac{< u'_i u'_j >}{< u'_k u'_k >} - \frac{1}{3}\delta_{ij} \quad For\ Isotropy : b_{ii} = 0$$

$$For\ RT :< u'_i\, u'_j >= 0,\ i \neq j$$

$$< u'_k\, u'_k >= \overline{u'^2} + \overline{v'^2} + \overline{w'^2} = 2\overline{u'^2} + \overline{v'^2}$$





RT Mix Measures – Energy Budget

TAMU Water Channel ~ 2002

- Energy budget
  - From the water channel Dissipation/PE ~ 0.49
  - From Youngs (1994) 3-D simulations Dissipation/PE~0.52

$$PE_i = \int_0^w \rho_{step} z\, dz \quad \Rightarrow \quad \int_0^{\frac{w}{2}} \rho_1 gz\, dz + \int_{\frac{w}{2}}^w \rho_2 gz\, dz$$

$$PE_f = \int_0^w \rho_{measured}\ z\, dz \quad \Rightarrow \quad \sum_{i=0}^{n} \rho_i g z_i \Delta z$$

$$PE_{released} = PE_i - PE_f$$

where, $\rho_{measured}$ *is the measured density, and* ρ_{step} *is the step-profile of density at the interface corresponding to the initial condition*

$$KE_i = 0 \qquad KE_{generated} = \tfrac{1}{2}\int_0^w \rho\, v'^2 dz$$

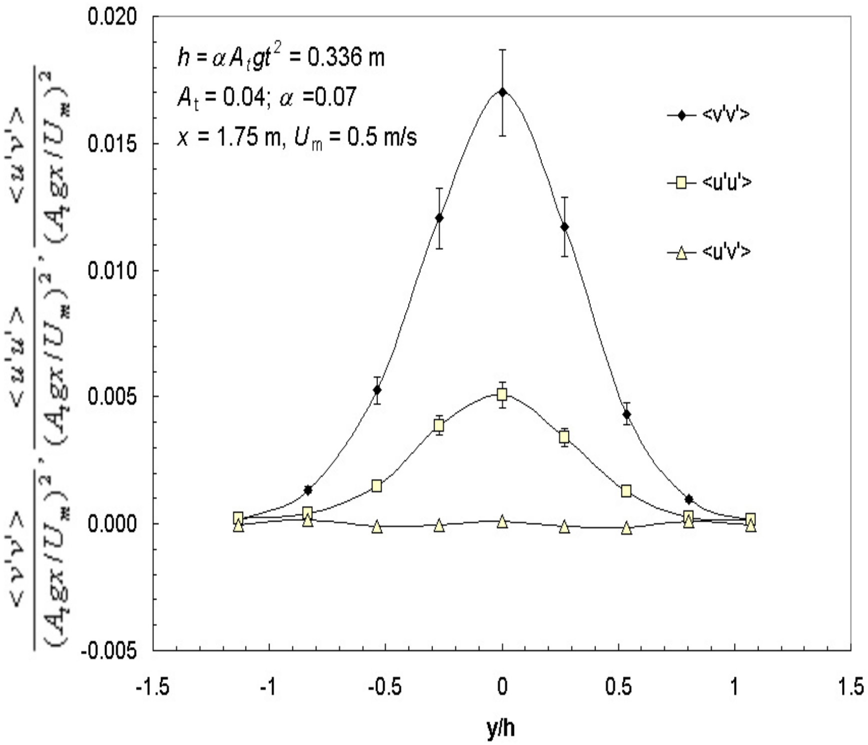
where, W = mix width, v' = rms velocity

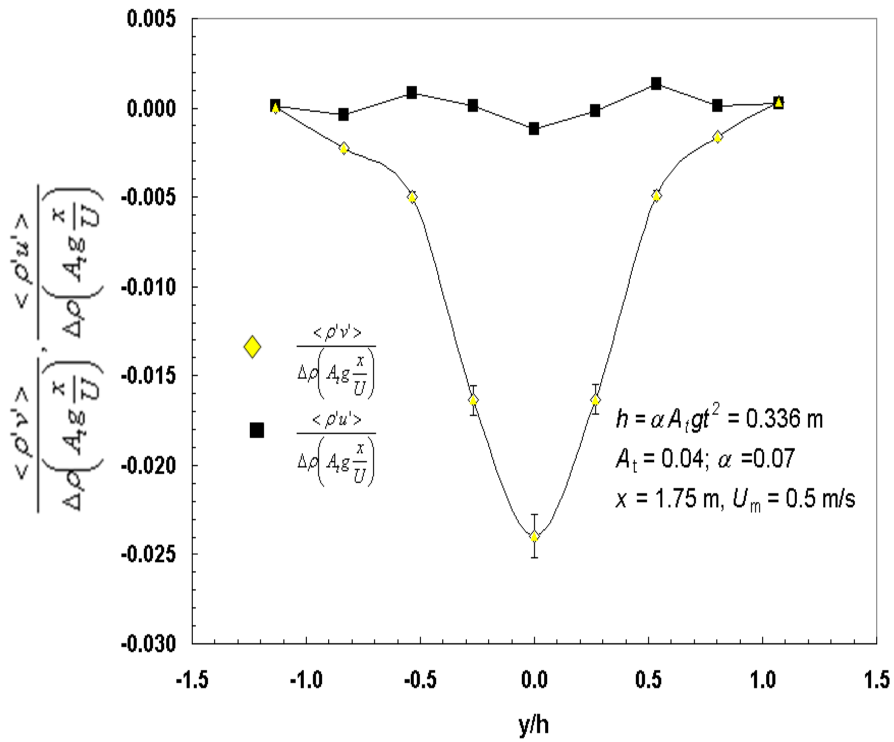
Dissipation, $D = PE_{released} - KE_{generated}$

$$\left| \frac{D}{PE_{released}} \right| = 0.49$$

RT Mix Measures

- Reynolds stresses and turbulent mass fluxes from the TAMU gas channel at late time (~ 2006) for models

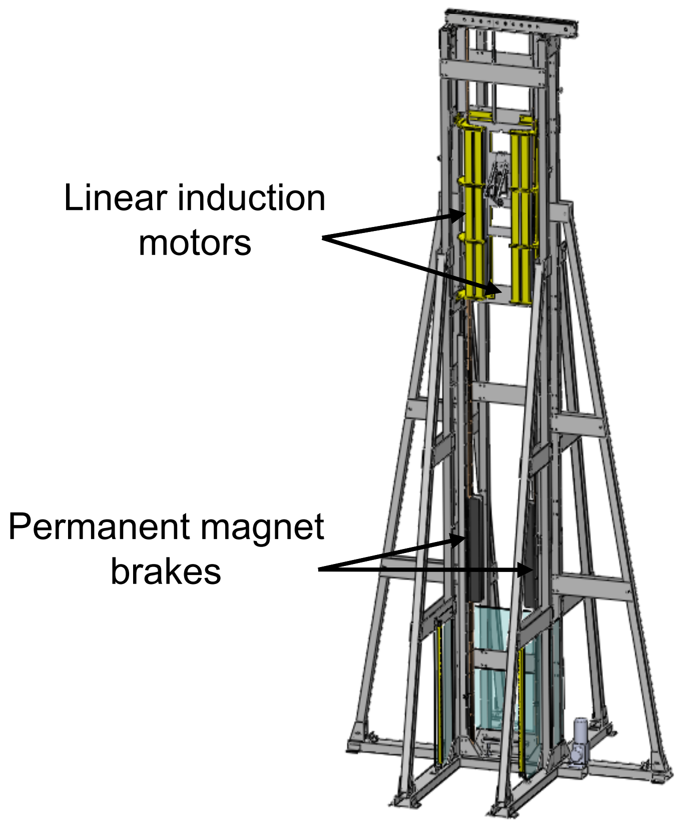


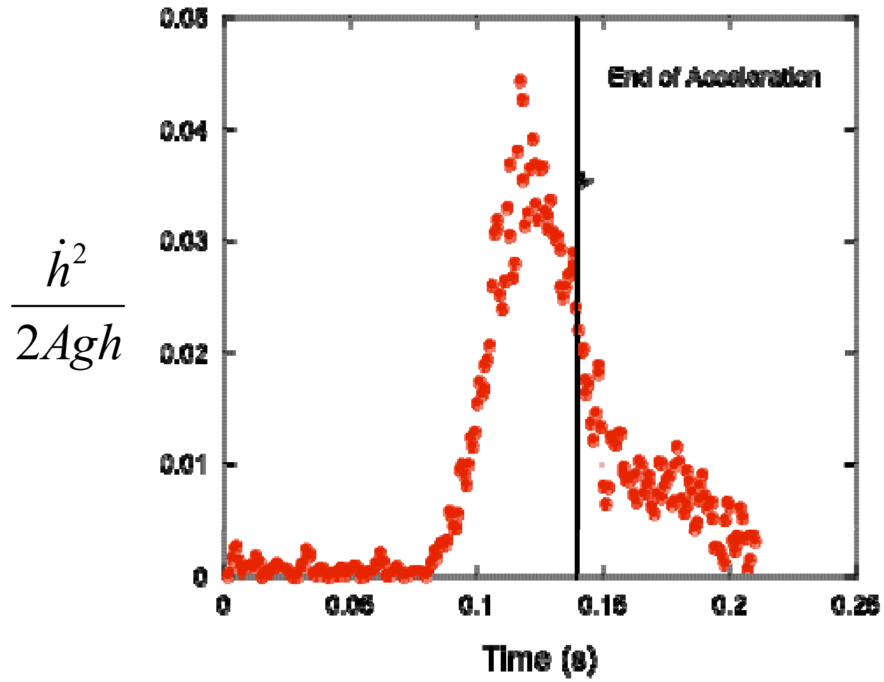


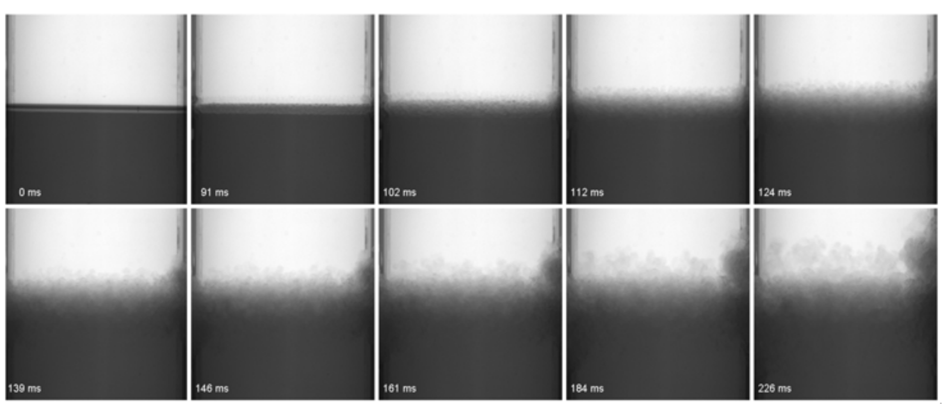
Non-dimensionalization by $A_t gt$, "free-fall" velocity

New Linear Induction Motor Apparatus

Prof. Jeff Jacobs, Univ. Arizona







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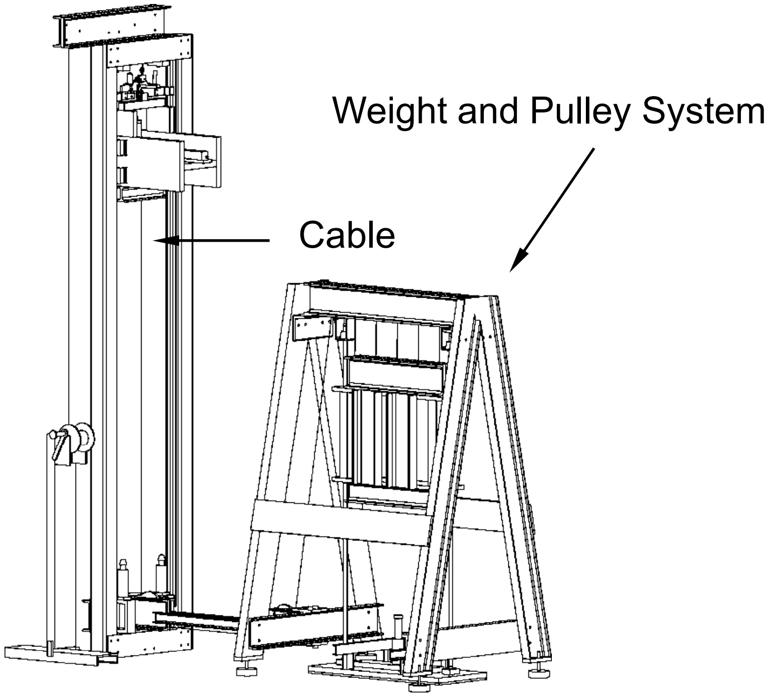
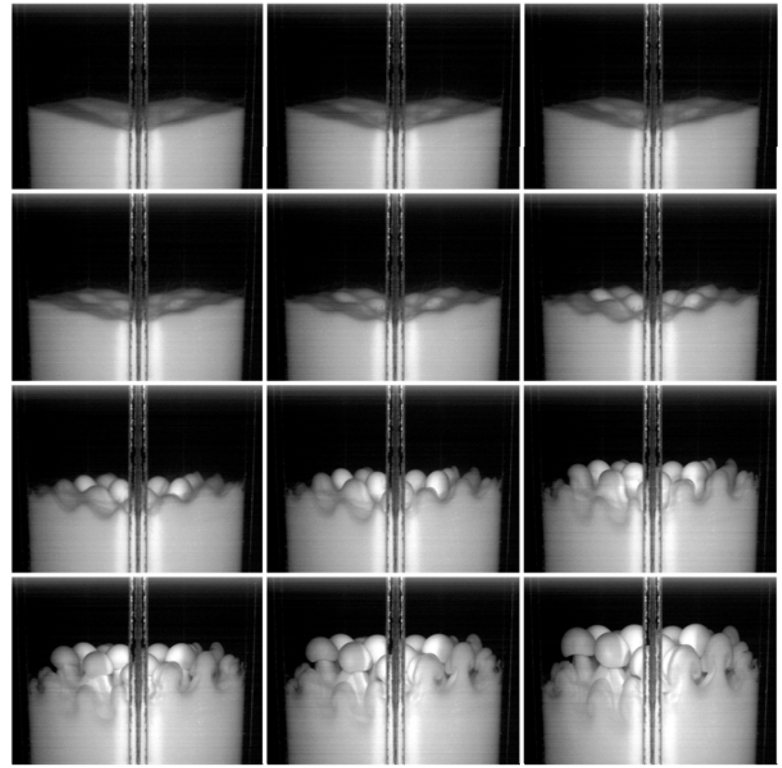
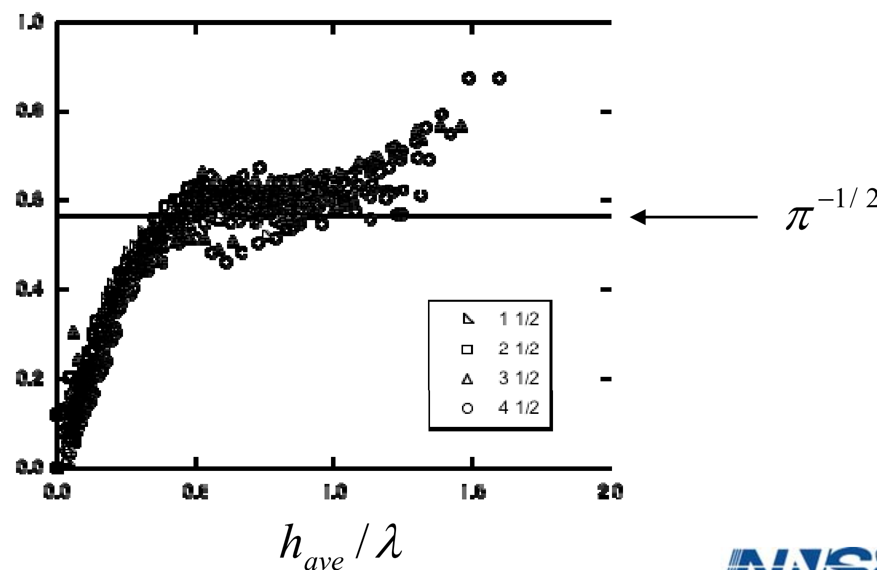
Atwood Machine





$$Fr_{ave} = \frac{U_{ave}}{\frac{1}{2}\left(\sqrt{Ag\lambda/(1+A)} + \sqrt{Ag\lambda/(1-A)}\right)}$$

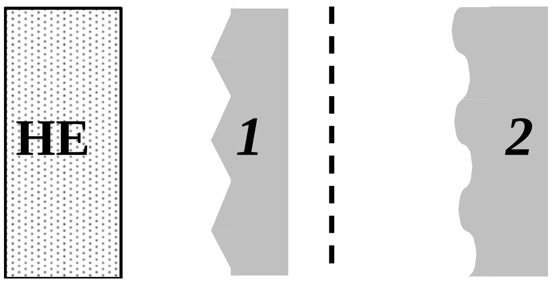


Prof. Jeff Jacobs, Univ. Arizona

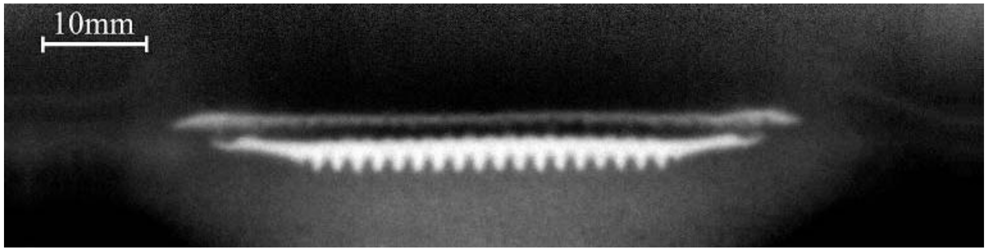
Method for recording of perturbation growth

Dr. Victor Raevsky

Shockless loading

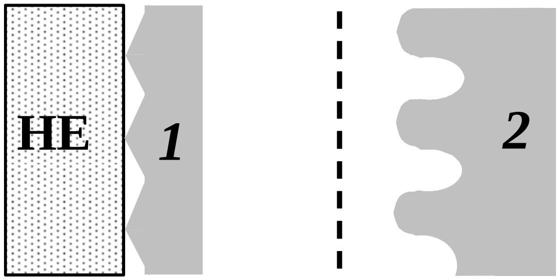


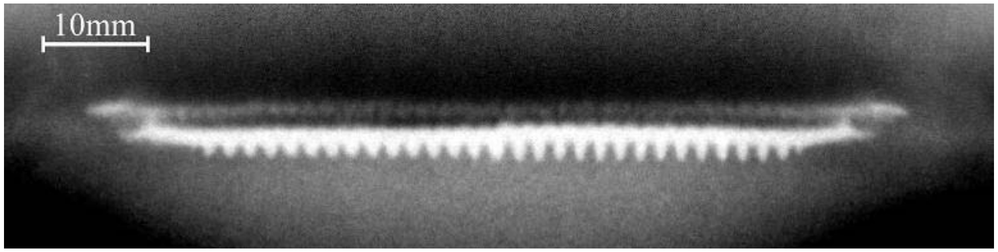
X-ray photos



Victor Raevsky

Shock-wave loading



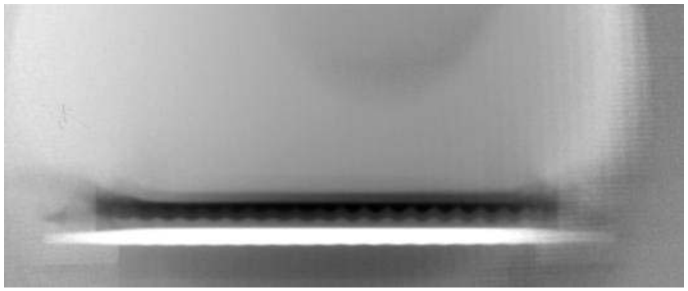


1 – investigated liner
2 – liner during loading

Proton radiography images

Dr. Victor Raevsky

1



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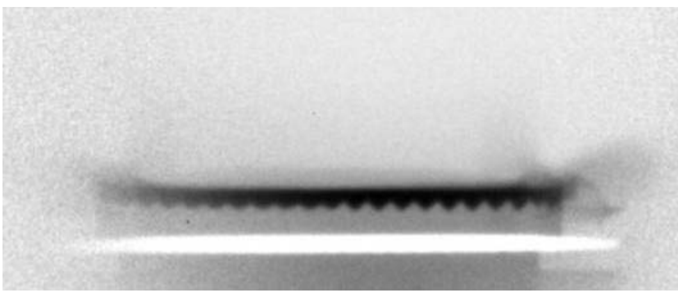

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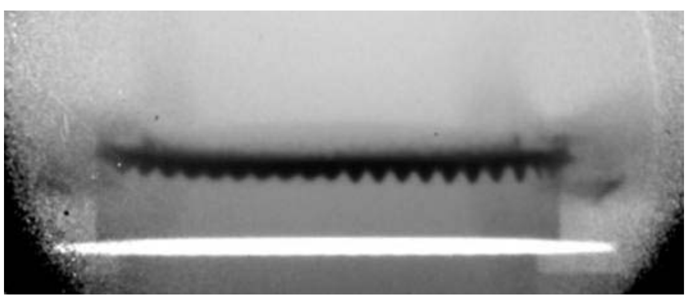

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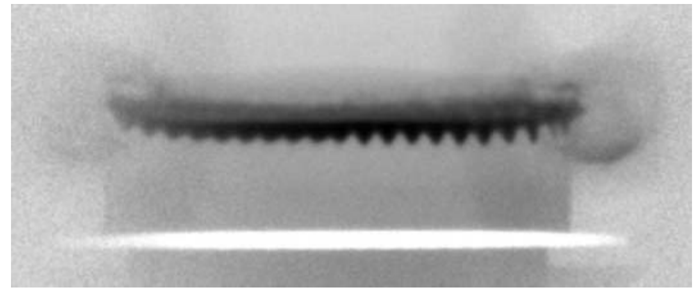

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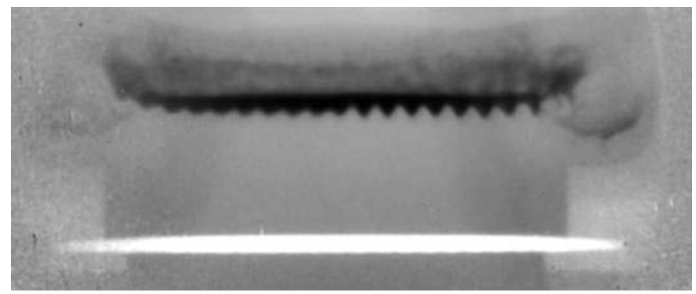

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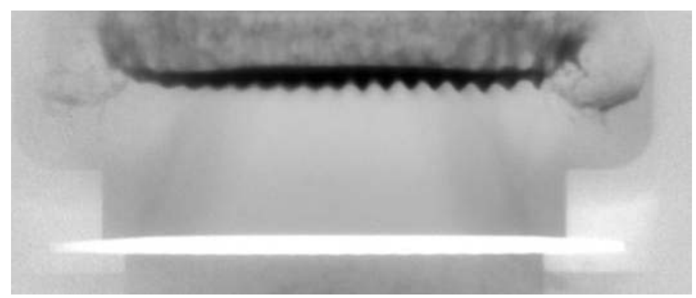
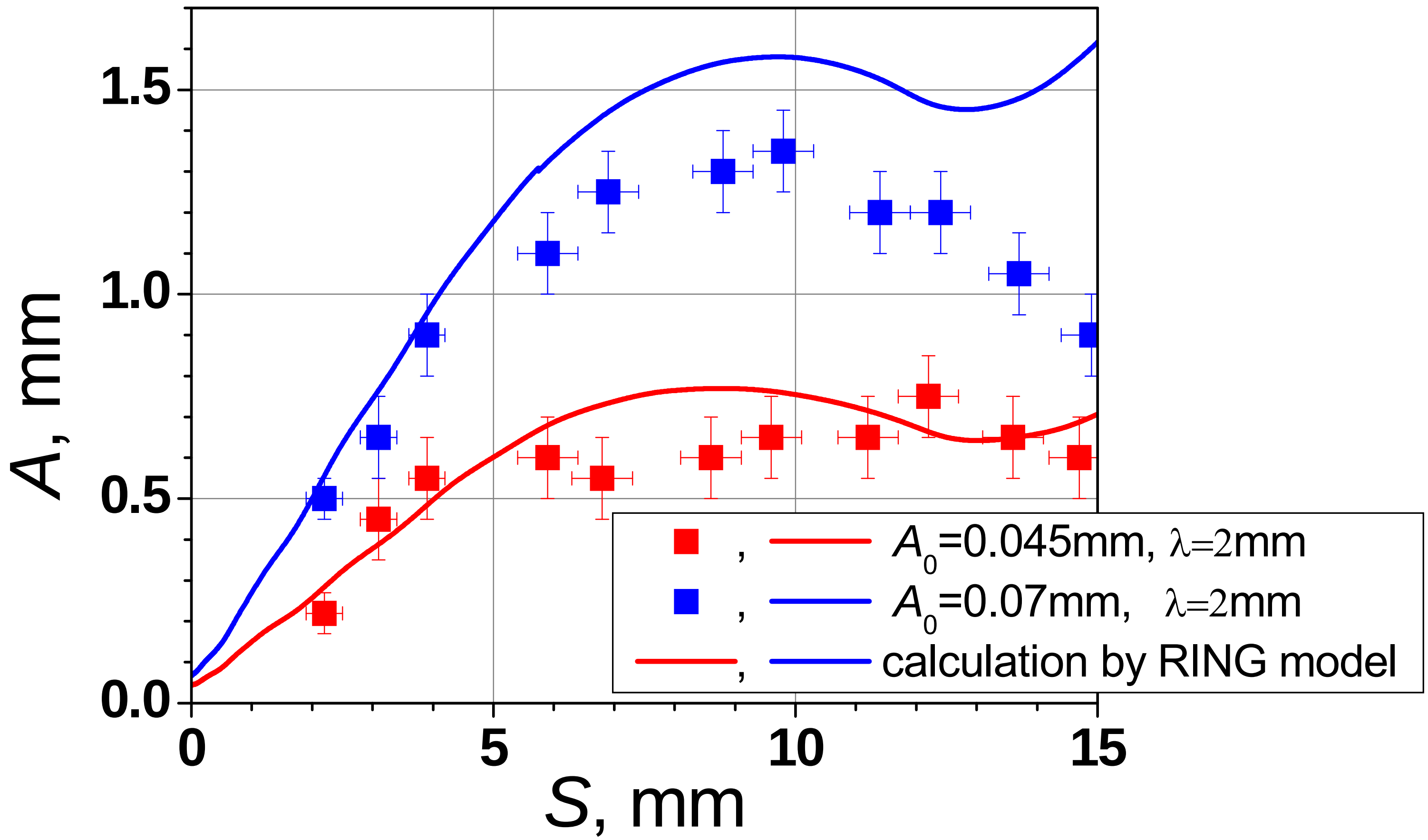


Perturbation growth

Dr. Victor Raevsky



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UW-Madison Rayleigh-Taylor Experiments Using Magnetic Liquids
Prof. Riccardo Bonazza

Magnetorheological (MR) Fluids

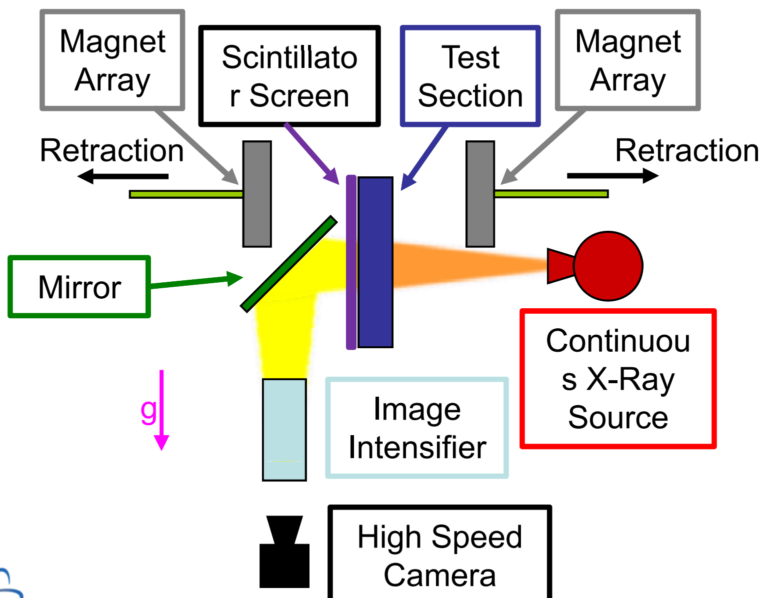
Flows as a viscous fluid except when subjected to an applied magnetic field

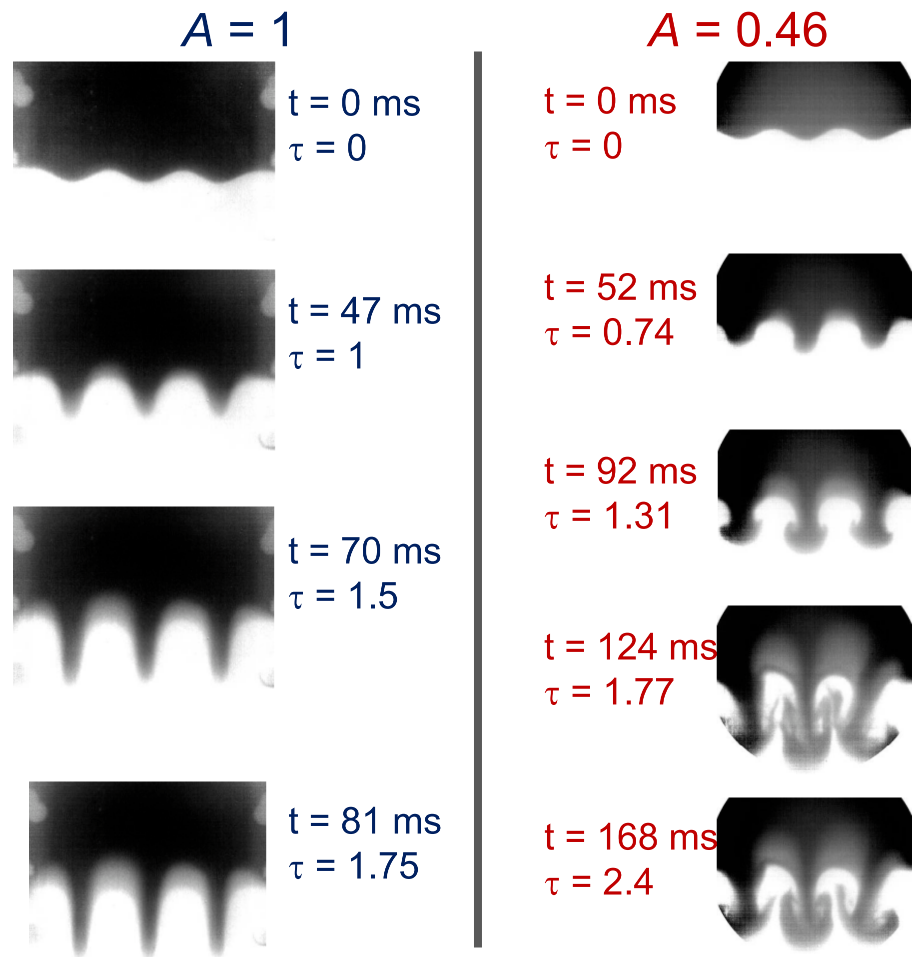
Fluid Pair	$A=\frac{\rho_1-\rho_2}{\rho_1+\rho_2}$	t' [s]	Re_{max}
MR-Water	0.46	0.07	~ 3,400
MR-Air	1	0.05	~ 10,300

Single Mode I.C.
$\eta/\lambda = 0.07$

$$t' =: \sqrt{\frac{\lambda}{Ag}} \qquad \tau = t/t' \qquad \mathrm{Re} = \frac{h_x \dot{h}_x}{\nu}$$

Schematic – Side View





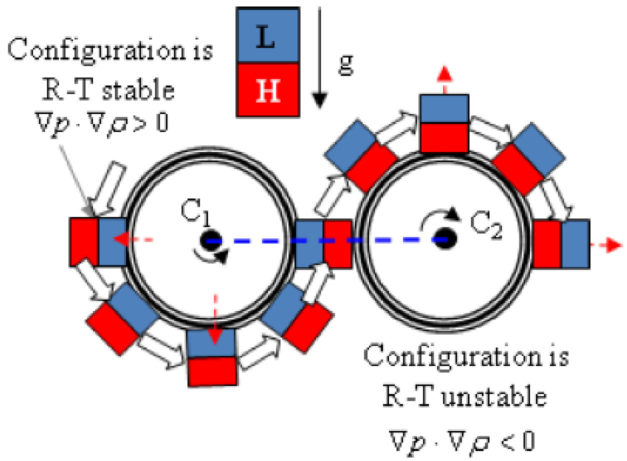
Velocities

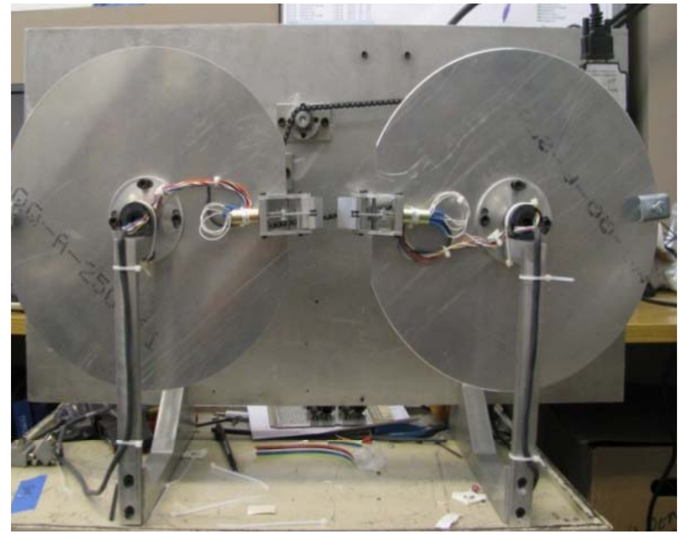
	$A=\frac{\rho_1-\rho_2}{\rho_1+\rho_2}$	Exp U_∞ [mm/s]	Oron U_∞^{2D} [mm/s]
Bubble	0.46	106	84
	1	92	105
Spike	0.46	209	138

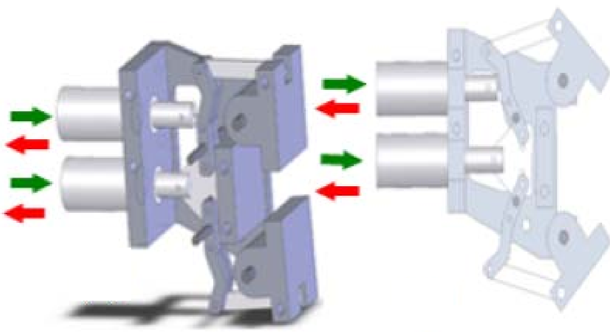
Two Wheel RT experiment (Proof of Concept)

Prof. Arindam Banerjee, Missouri S&T (formerly UM-Rolla)

Use Centrifugal Forces - Transfer Test Unit wheel 1 to wheel 2

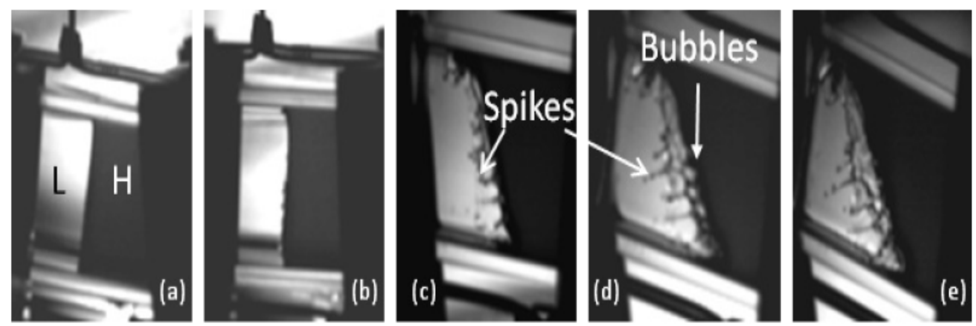






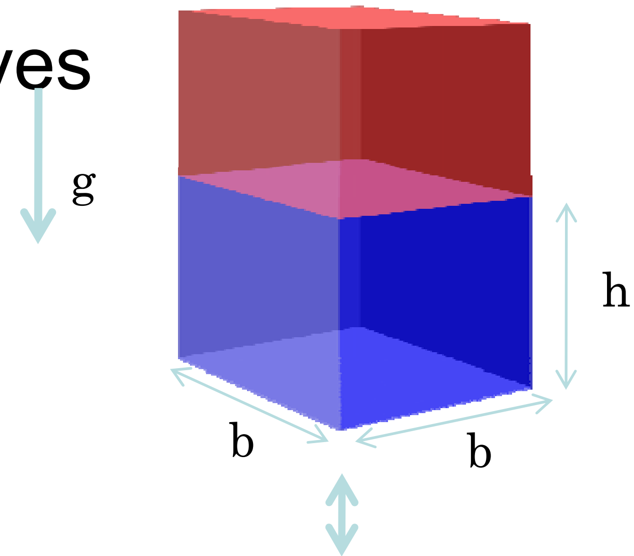
Solenoid actuated transfer claws

POC runs with Surfactants (AOT) – Air/Water – A_t #=0.99



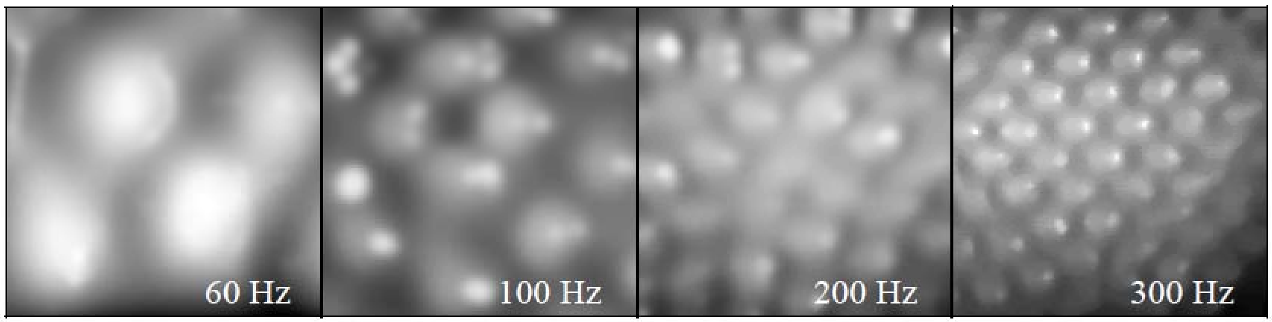
1 ft diameter wheels for PoC setup– the full scale experiment will have 8 ft dia. wheels
For N=250 rpm, the mechanism would impart ~ 100 g forces on the 2 fluid interface

Controlled ICs by Faraday Waves



- Faraday waves are being used to seed initial conditions (ICs) for the miscible RT experiments. The generation of Faraday waves allows precise control and accurate measure of spectral components of ICs useful in computational studies and model verification (Olson & Jacobs, PoF-2009).
- PoC exercise - a square container is oscillated vertically to incite Faraday waves at the immiscible fluid interface using an amplifier and a speaker.
- Faraday waves to be excited at the onset of transfer.

Plan View of 2-fluid (immiscible) interface



Future Directions for the 2 wheel Experiments :

- ✓ High Atwood number (miscible) experiments using ICs with controlled ICs
- ✓ Effect of impulsive acceleration
- ✓ De-mix experiments

Funding Agencies: NSF-CBET (Fluid Dynamics), LANL

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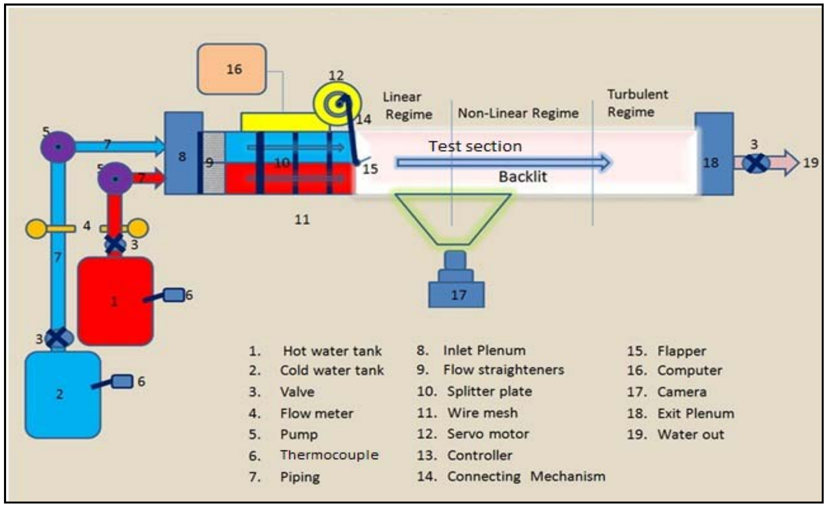
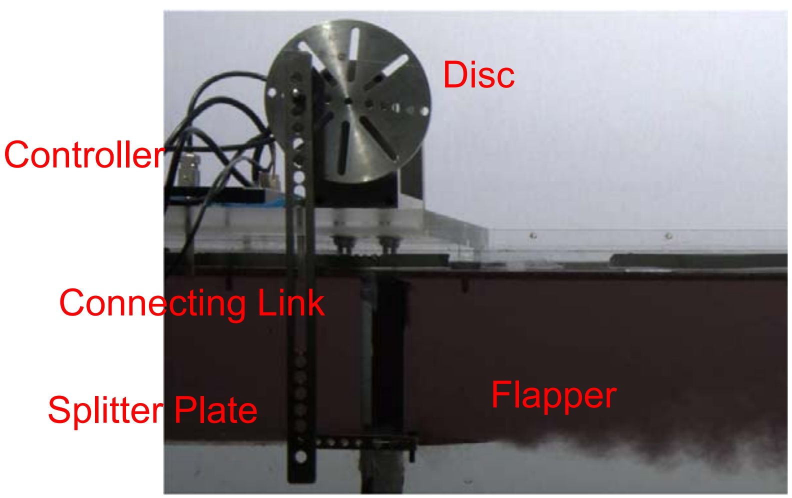
Low-Atwood Number Experiments- Effect of IC

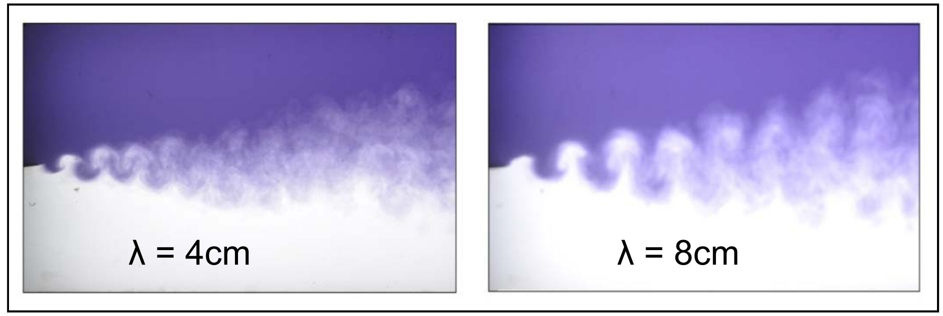
Prof. Devesh Ranjan, Texas A&M Univ.

Schematic of the channel



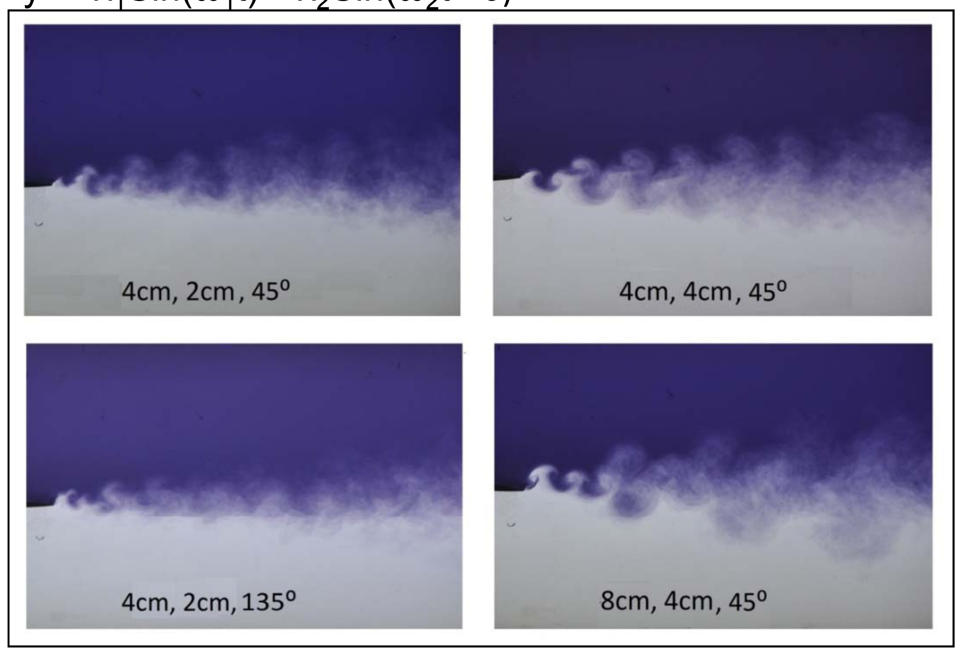


Single mode experiments: Atwood number ~ 9e^{-4}



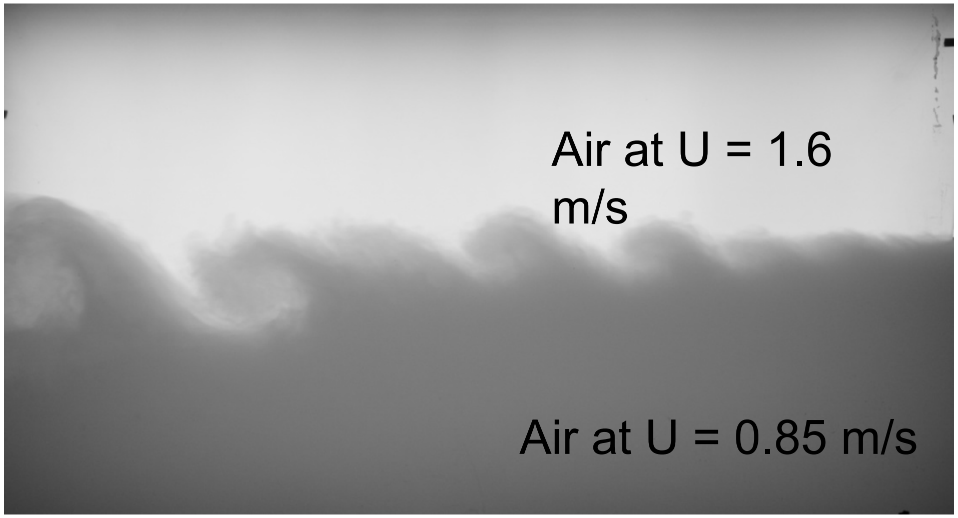
Binary mode experiments: Atwood number ~ 7-8e^{-4}

Each experiment designated by (λ_1, λ_2, θ) such that
$y = \lambda_1 \mathrm{Sin}(\omega_1 t) + \lambda_2 \mathrm{Sin}(\omega_2 t + \theta)$

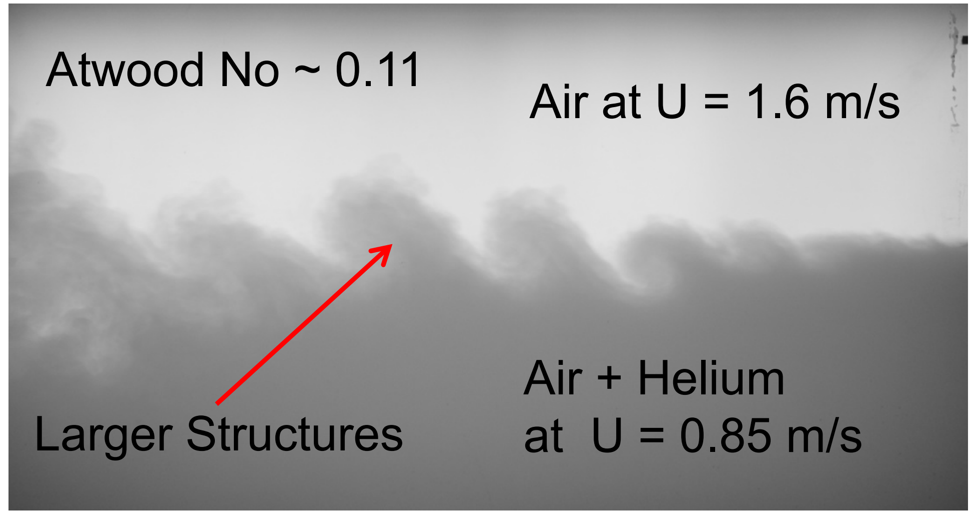


Effect of Shear on R-T experiments at high Atwood Numbers

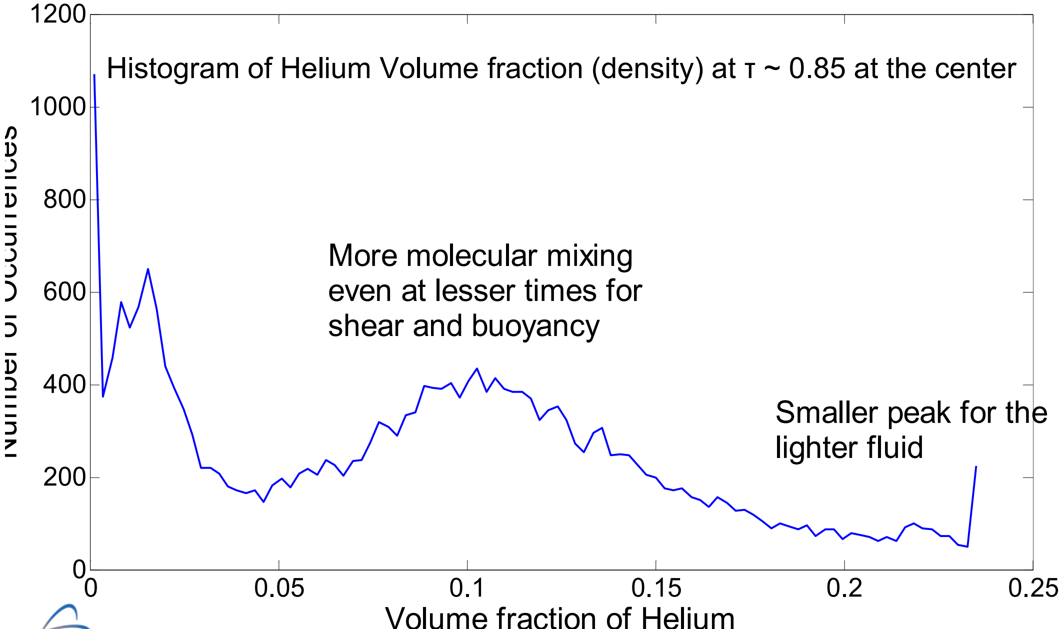
Prof. Devesh Ranjan, Texas A&M Univ.



Typical image With Shear without Buoyancy



Typical image With Shear and Buoyancy



<u>Richardson Number</u>

$$Ri = -2hg\frac{\Delta\rho}{\rho}/\Delta U^2$$

- Provides measures for studying the influence of shear and buoyancy on the mixing plane
- Channel suitable for running experiments for various values of Richardson number (up to Ri~10)

<u>Future Work</u>

- Implement the PIV-PLIF system and acquire the turbulence statistics data for RT growth with shear
- Implement the Flapper mechanism in the Gas-Channel Facility
- Three-fluid RT mixing experiments

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RT Research Challenges

- Single and multi-mode RTI experiments with well characterized initial conditions are still needed for code validation, and to late time ($A/\lambda >> 1$).
- Additional physical effects (e.g. viscosity, surface tension, Sc, strength).
- Non-planar geometries.
- High Atwood number effects still need some work.
- Extended late time ($A/\lambda >> 1$) seems to have been neglected, but recent work by Ramaprabhu suggests a re-acceleration.
- Detailed measurements for Accel/Decel (& demix).
- Detailed measurement for complex multi-fluid configurations.
- 2-D and 3-D turbulent mix problems.
- Coupled processes – RT/RM/KH.

THANKS