The Influence of Gravity on Physicochemical Systems

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- **Introduction: acceleration- terrestrial and planetary gravity, weightlessness, 'effective gravity', microgravity,**
- **Buoyancy: common processes affected by gravity**
- **Effects of 'steady acceleration' on fluid motion:**
  - **Density variations in liquids and gases – thermal and solutal buoyancy**
  - **Free surfaces and interfaces of liquids**

Residual acceleration or g-jitter effects on fluid motion and transport

  - **Instantaneous system responses**
  - **Mean flow generation**
- **Summary**

Symbols

G ~ gravitational constant

g_0 ~ 9.8 m/s^2

Me ~ mass of the earth

Gr ~ Grashof number: ratio of buoyant to viscous forces = $\beta \Delta T g L^3 / \nu^2$,

β= coefficient of thermal expansion [K^{-1}]

ΔT = characteristic temperature difference [K]

L = characteristic length scale [m]

ν= kinematics viscosity [m/s^2]

κ = thermal diffusivity [m/s^2]

D = diffusivity [m/s^2]

Pr ~ Prandtl number = kinematics viscosity / thermal diffusivity = ratio of thermal and momentum diffusion timescales, Pr = ν/κ

Ra ~ Rayleigh number: ratio of conductive heat transfer and convection timescales, Ra = GrPr

Rav = vibrational Rayleigh number characterizes ratio of conductive heat transfer and mean convective flow time scales, Rav = $(\beta \Delta T b \omega L)^2/2\kappa\nu$

St = dimensionless frequency, St = $\omega L^2/\nu$

Ω= dimensionless frequency, Ω = $\omega L^2/\kappa$

Sc ~ Schmidt number = ratio of species and momentum diffusion timescales, Sc = ν/D

B = Bond number = ratio of gravity forces and surface tension forces, B = $\rho g L^2/\sigma$

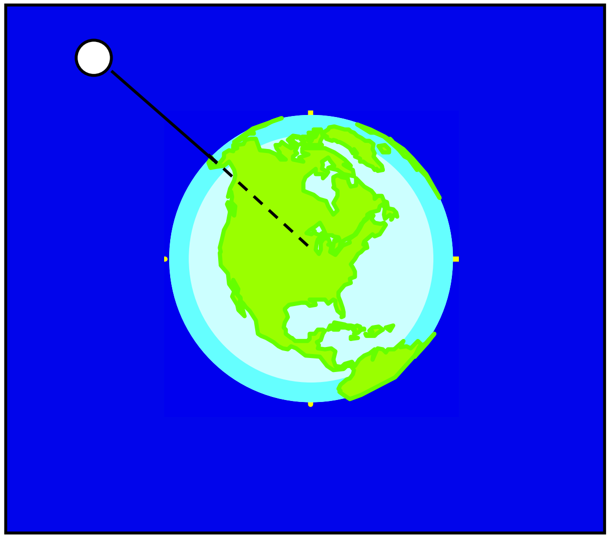
σ = surface tension

Pe = Peclet Number = ratio of crystal growth velocity and characteristic diffusion speed, Pe = $V_g L/D$

V_g = crystal growth velocity

Nu = Nusselt Number = ratio of convective heat transfer and conductive heat transfer

Gravitational acceleration



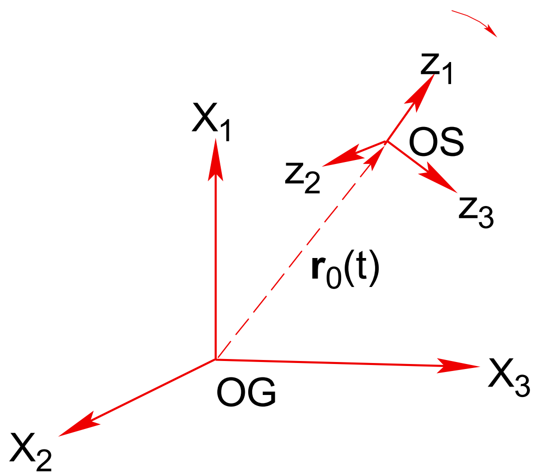
$$a_g = -\frac{GM_e}{r^2}$$

$$G = 6.673\times10^{-11}\,m^3\,kg^{-1}s^{-2}$$

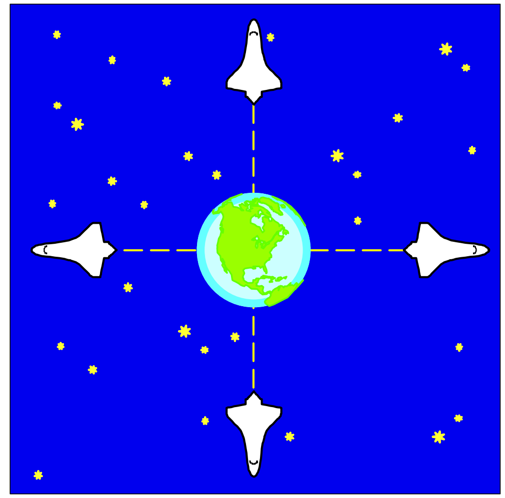
$$M_e = 5.976\times10^{24}\,kg$$

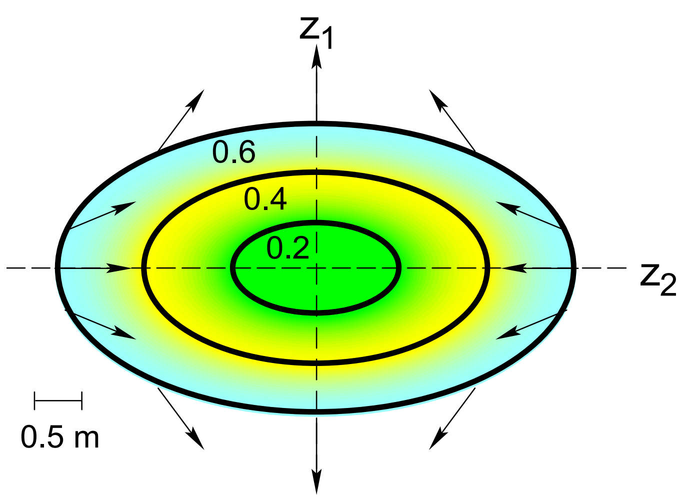
	altitude km	acceleration [m/s^2]	
Earth	0	9.80308	100.00%
	1	9.80001	99.97%
	5	9.78773	99.84%
	8.85	9.77593	99.72%
	10	9.77548	99.72%
Spacelab	325	8.87551	90.54%
ISS	425	8.61650	87.90%
Moon	0	1.62592	

'Effective gravity in low earth orbit'



Reference Frames





Isoacceleration Surfaces [µg]

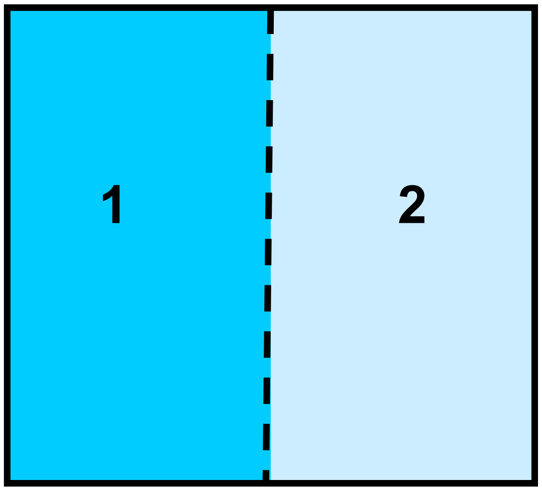
The gravity gradient stabilized type attitude motion will yield a quasi-steady acceleration that varies in orientation and magnitude with distance from the spacecraft mass center

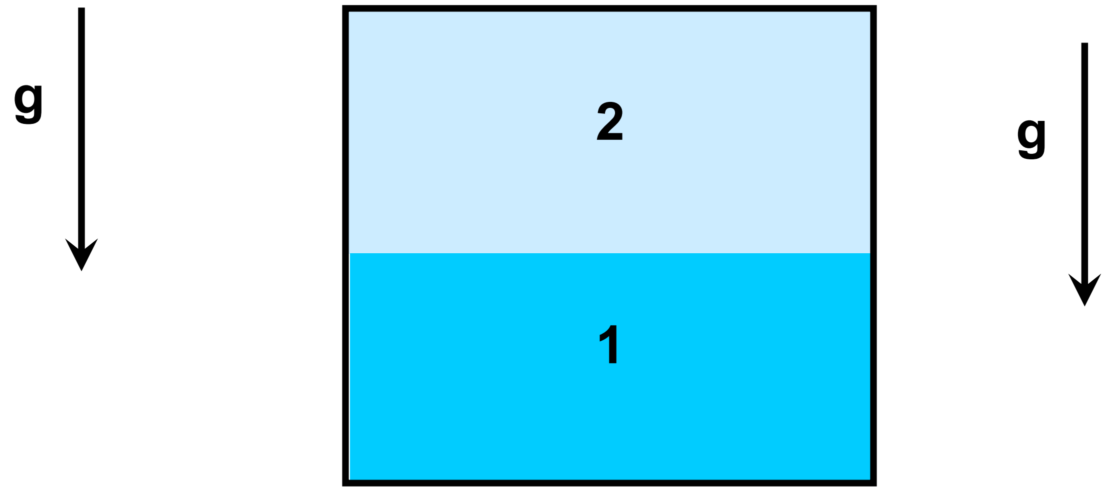
Buoyancy

Gravity affects the state of fluid matter and exerts a major influence over mass, heat and momentum transfer in systems where fluids are prevalent

The degree to which gravity, or any similar body force affects fluid processes will depend whether the density distribution is uniform or not and how the density gradient is oriented with respect to the gravity vector. In this tutorial I will discuss how gravity as experienced at the earth (or other planetary surfaces) can affect transport and on the nature of the microgravity environment and how it can generate fluid motions (even under near weightless conditions) and, thus, influence transport of heat and mass

Effects of ‘steady acceleration’ on fluid motion: isothermal density stratification





Two immiscible fluids initially separated by a partition

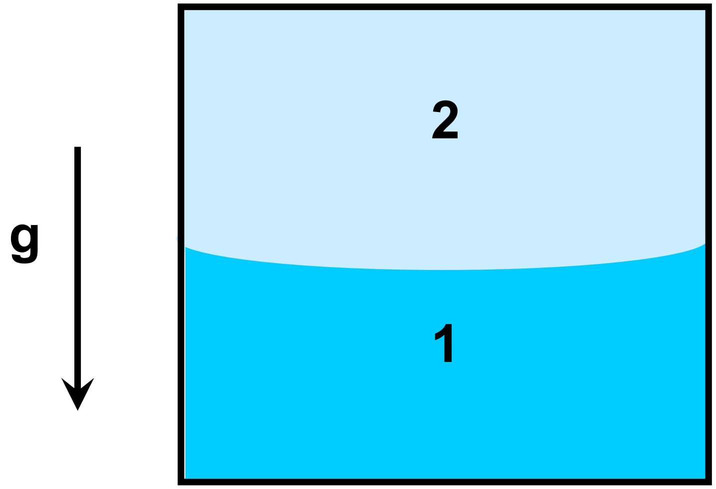
liquid 1 has a large density than liquid 2

$$\rho_1 > \rho_2$$

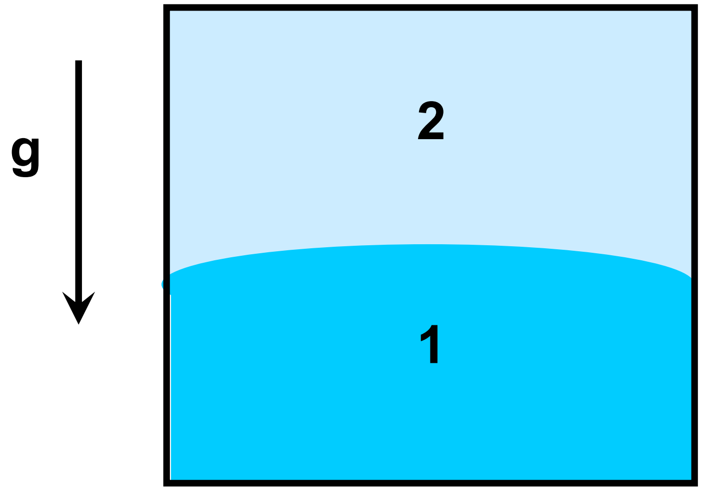
When the partition is removed the liquids will reorient so that the interface is level and the denser liquid lies below the interface

In an isothermal stratified fluid, surfaces of equal density will <u>generally</u> orient themselves to be perpendicular to gravity and with density decreasing upward.

Near the walls surface tension may cause deviations from the horizontal surface…



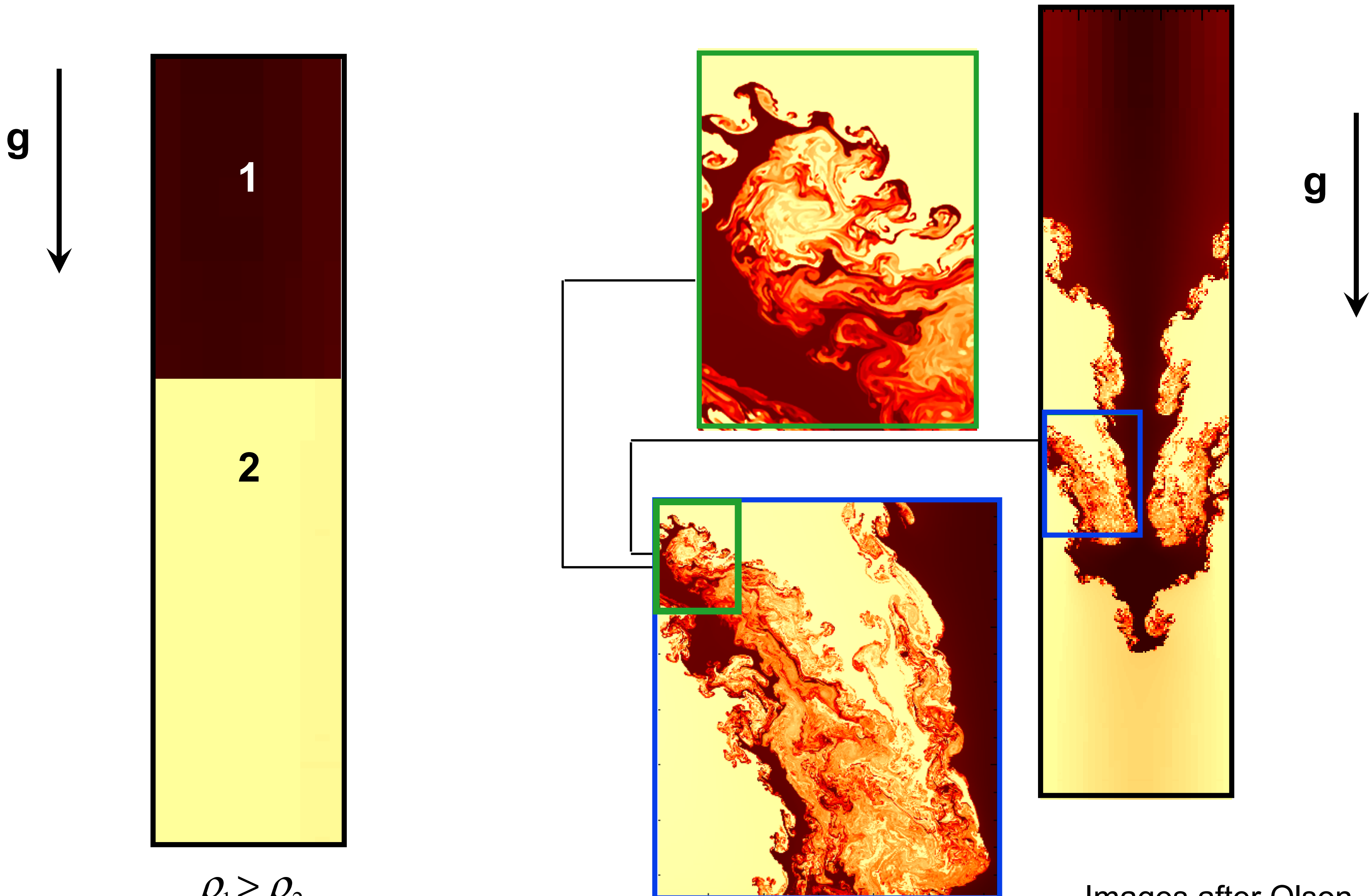
Surface tension generally bends the interface near walls. The direction of bending depends on the interfacial tension and which liquid prefers to wet the container walls



Here fluid 2 prefers to wet the walls and displaces fluid 1 downward near the walls

In both cases the surface is nearly perpendicular to the gravity vector away from the walls and the denser liquid always lies below the interface

Rayleigh-Taylor instability in miscible liquids

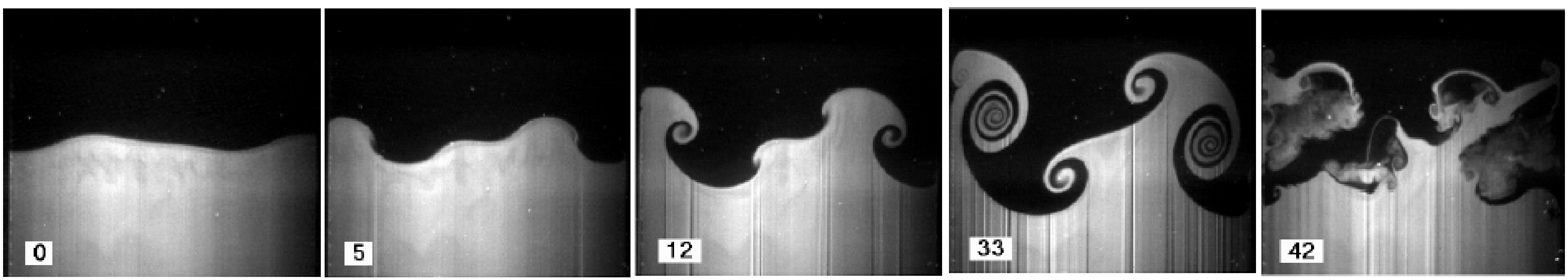


$\rho_1 > \rho_2$

Images after Olson, 1999
U. Chicago

Effects of sudden acceleration on motion: Richtmeyer-Meshkov instability

- **Richtmyer-Meshkov (RM) instability occurs when two fluids of different densities are impulsively accelerated normal to their nearly planar interface.**
- **A fundamental fluid instability and is importance in fields ranging from astrophysics to material processing.**
- **RM instability normally carried out in shock tubes using gases, & generation of a sharp well-controlled interface is difficult → scarcity of good experimental visualizations**



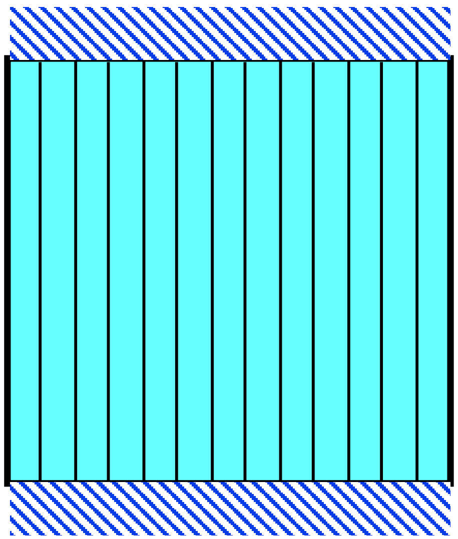
Niederhaus & Jacobs (1998)

Effects of ‘steady acceleration’: nonisothermal density stratification

Fluid density is a linearly decreasing function of temperature

0-g

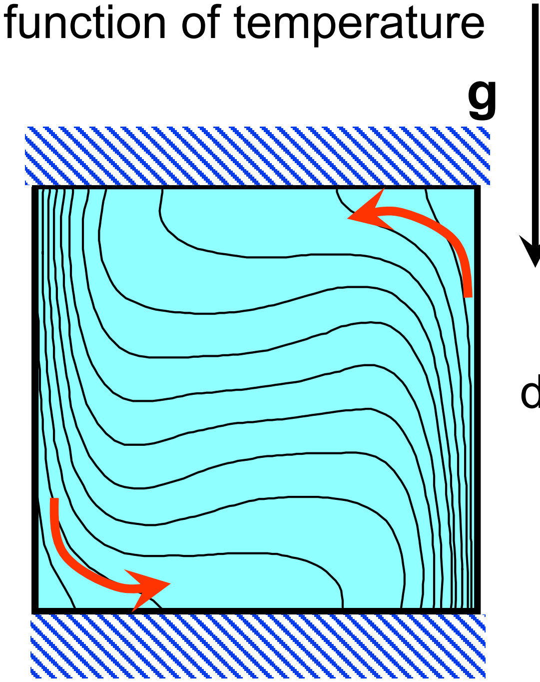
T_{COLD}



T_{HOT}

cooler, denser fluid sinks at the cold wall

g



Hotter, less dense fluid rises at the hot wall

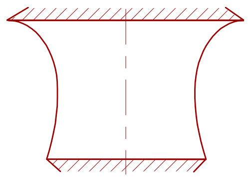
Insulated top and bottom boundaries

Isotherms (here = density contours) attempt to reorient perpendicular to gravity vector with lighter fluid below

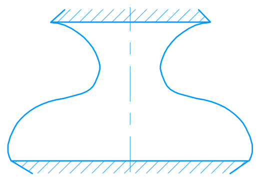
Distortion of isotherms from vertical straight lines is a function of Rayleigh number:

$$Ra = \frac{\beta\left(T_{HOT} - T_{COLD}\right) g L^3}{\kappa \nu} \rightarrow \frac{\text{Characteristic time for conductive heat transfer}}{\text{Characteristic time for momentum transfer}}$$

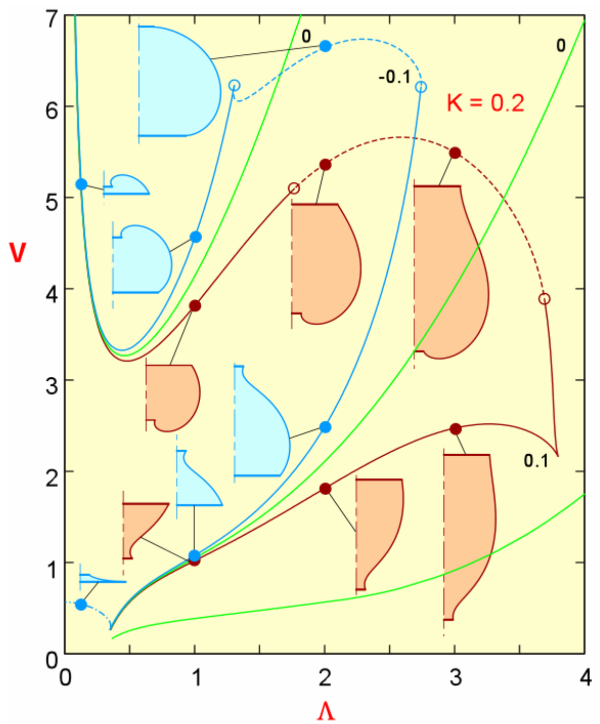
Effects of ‘steady acceleration’ on fluid motion: Liquid interfaces and free surfaces- liquid bridges

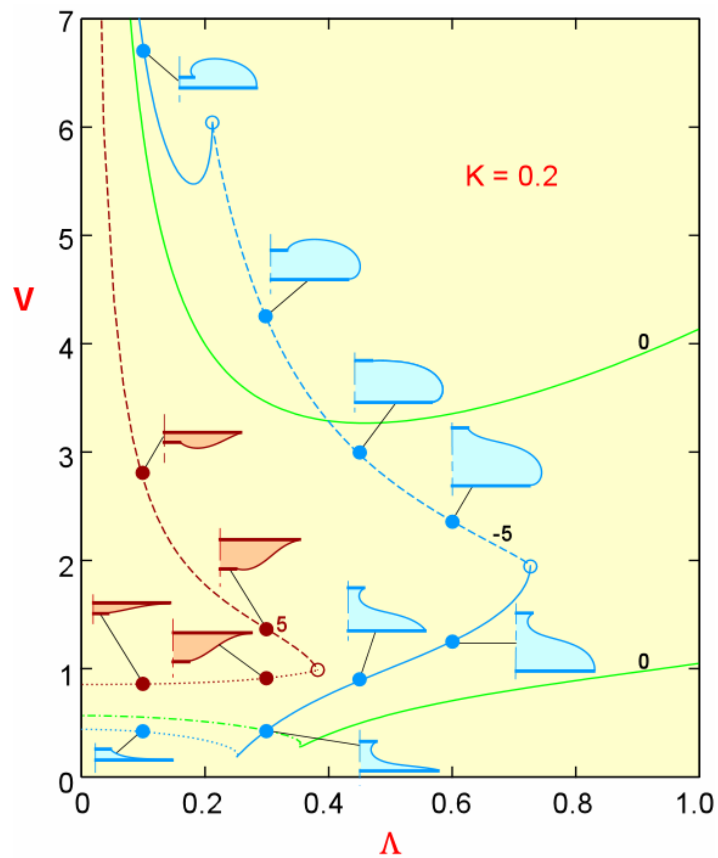


B > 0



B < 0

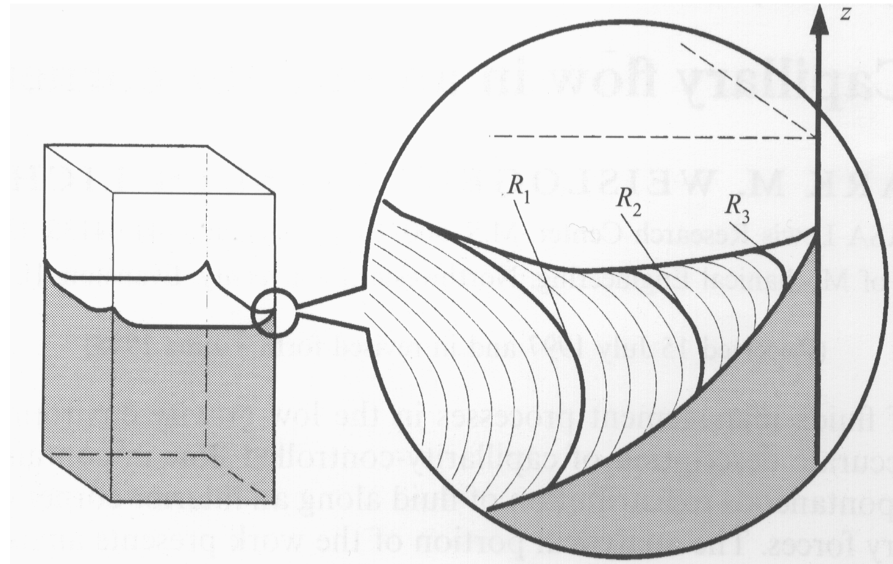




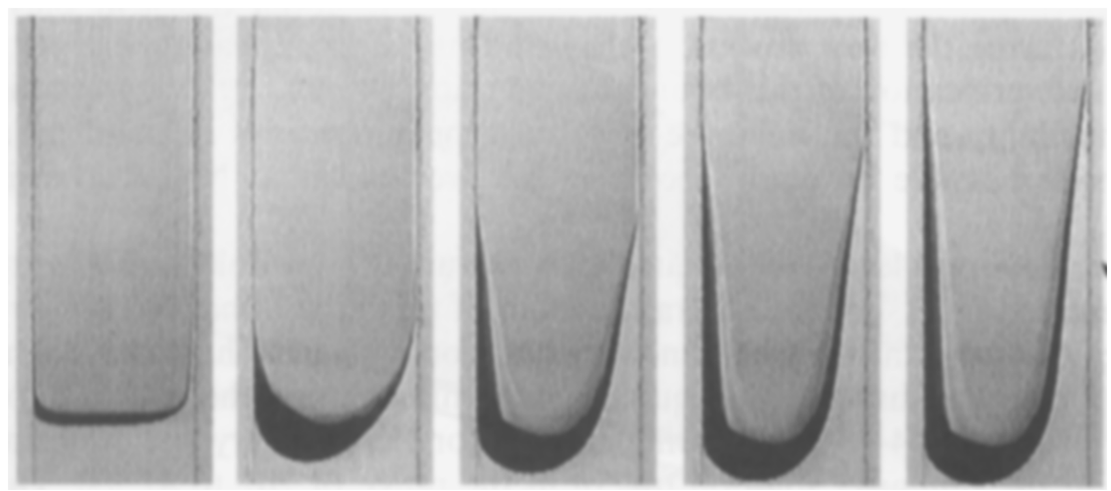
V_{act} = volume/π* r^2h
K = ratio of the small disk to the largest gradient
Λ = h/2* r
r = mean radius and B = Bond number

Surface tension-driven flows

- Near corners interfaces are forced to curve
- The pressure difference $p_1 - p_2$ is inversely proportional to surface mean curvature



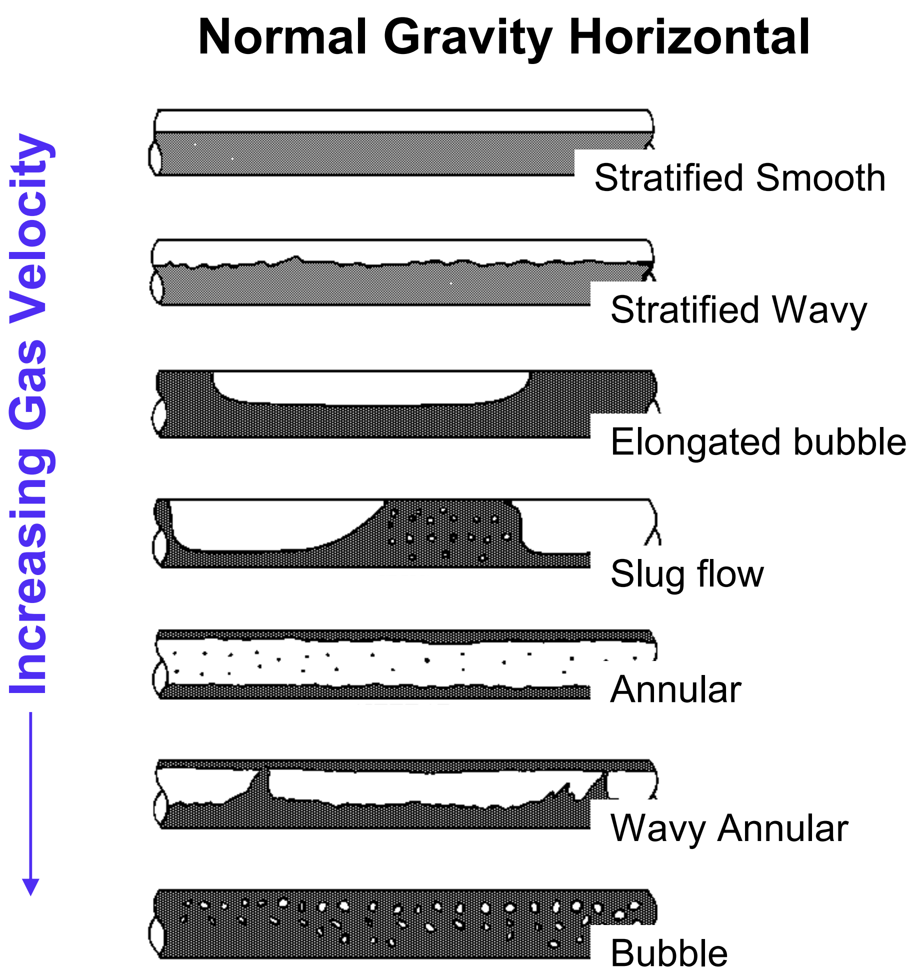
1-g → **low-g**

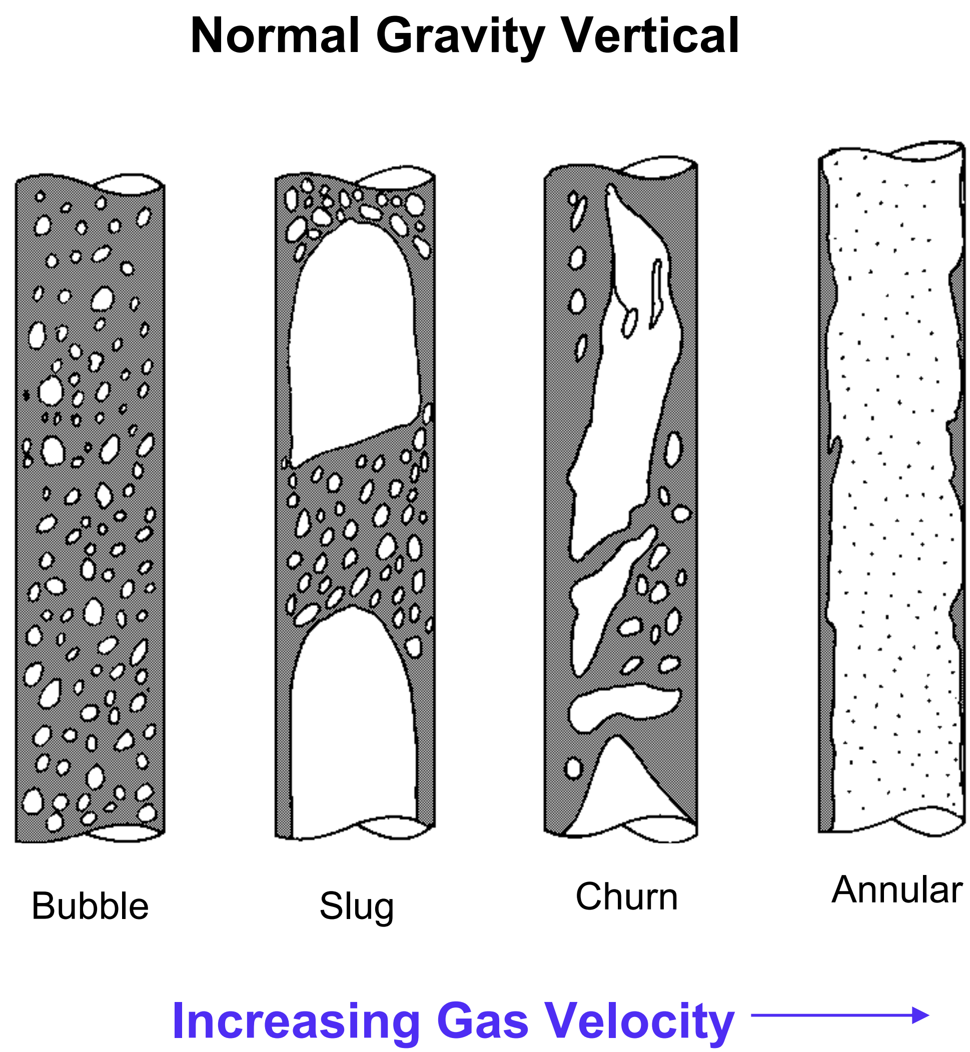


time →

Zero gravity - pressure gradient not hydrostatically balanced - ⇒ narrow columns of liquid pumped up the corners by surface-tension forces

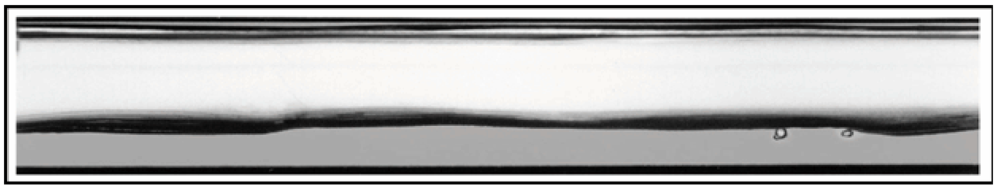
Effect of Gravity on Gas-Liquid flow





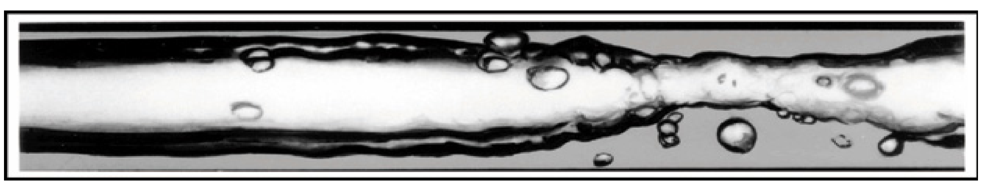
Effect of Gravity on Gas-Liquid flow

1 g



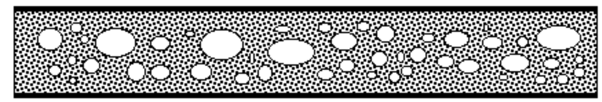
Stratified Flow

Stratified Wavy Flow

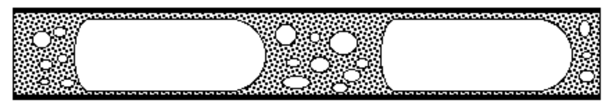


Slug-Annular Flow

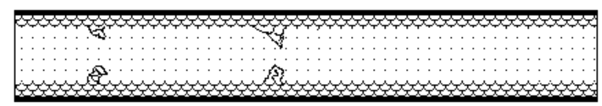
Reduced Gravity



Bubble Flow

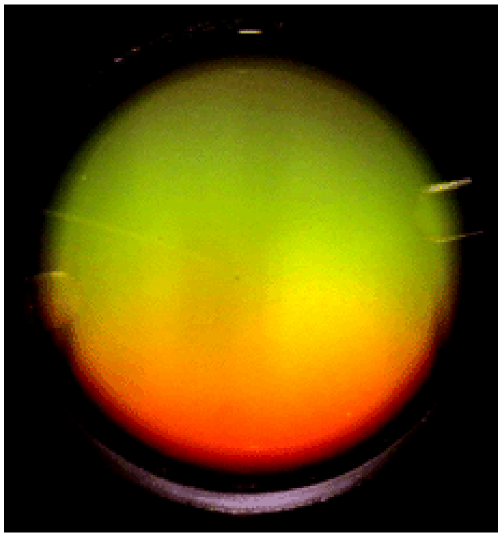


Slug Flow

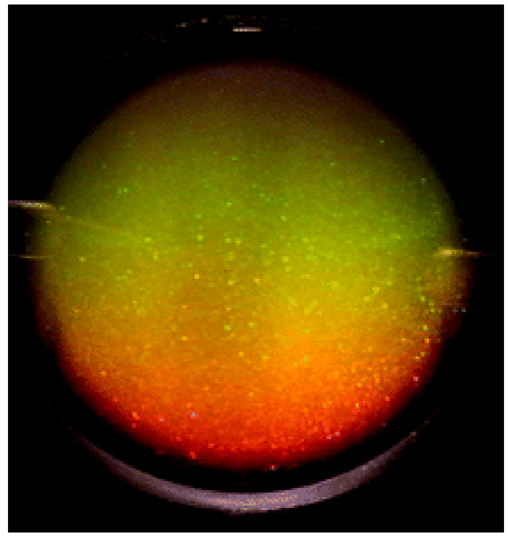


Annular Flow

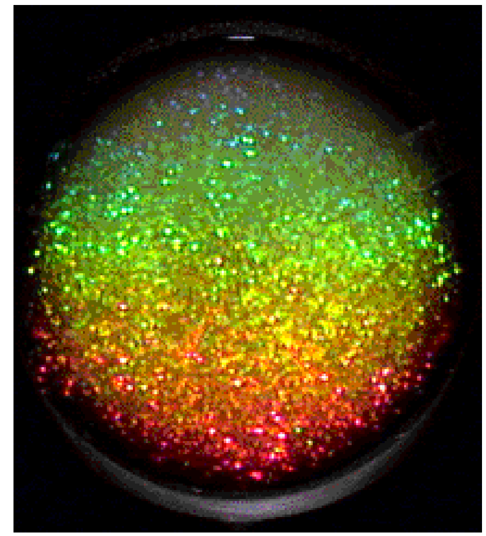
Detrimental effects of sedimentation and convection are eliminated in microgravity



μg
disordered fluid
random particle motion



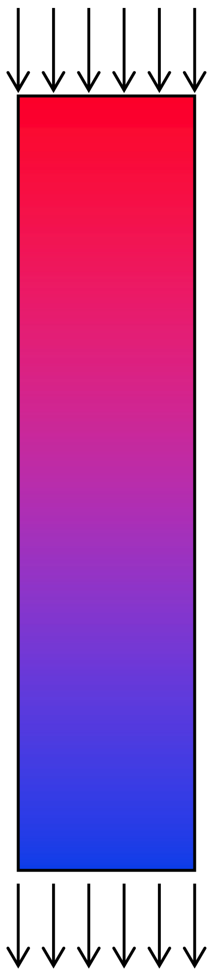
μg
Nucleation



μg
Crystallization

- Results from **PHASE** surprised the condensed matter physics community. Large dendritic crystals were produced that were previously undetected in ground-based studies.
- Industrial relevance: **semiconductors**, **electro-optics**, **ceramics**, and **composites** leading to progress toward development of **new materials**

Steady acceleration: effects on directional solidification

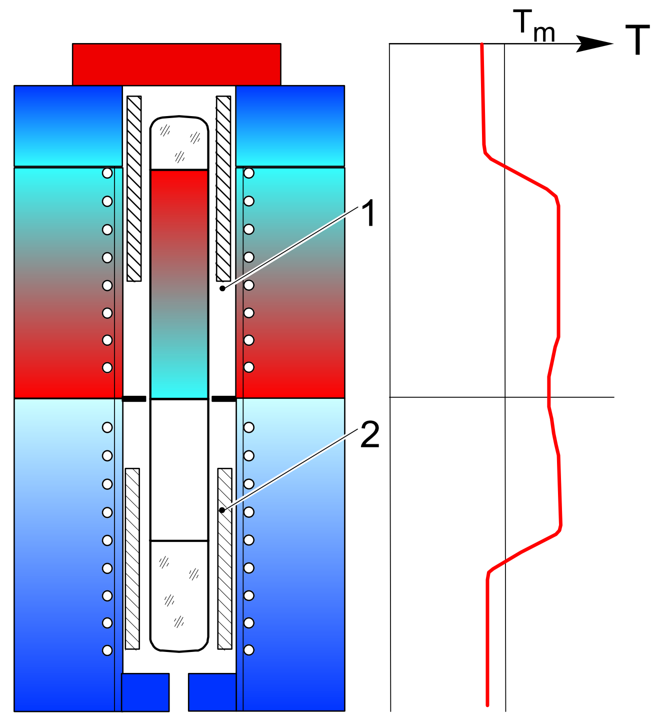


T_{HOT}

T_{MELT}

Crystal-melt interface

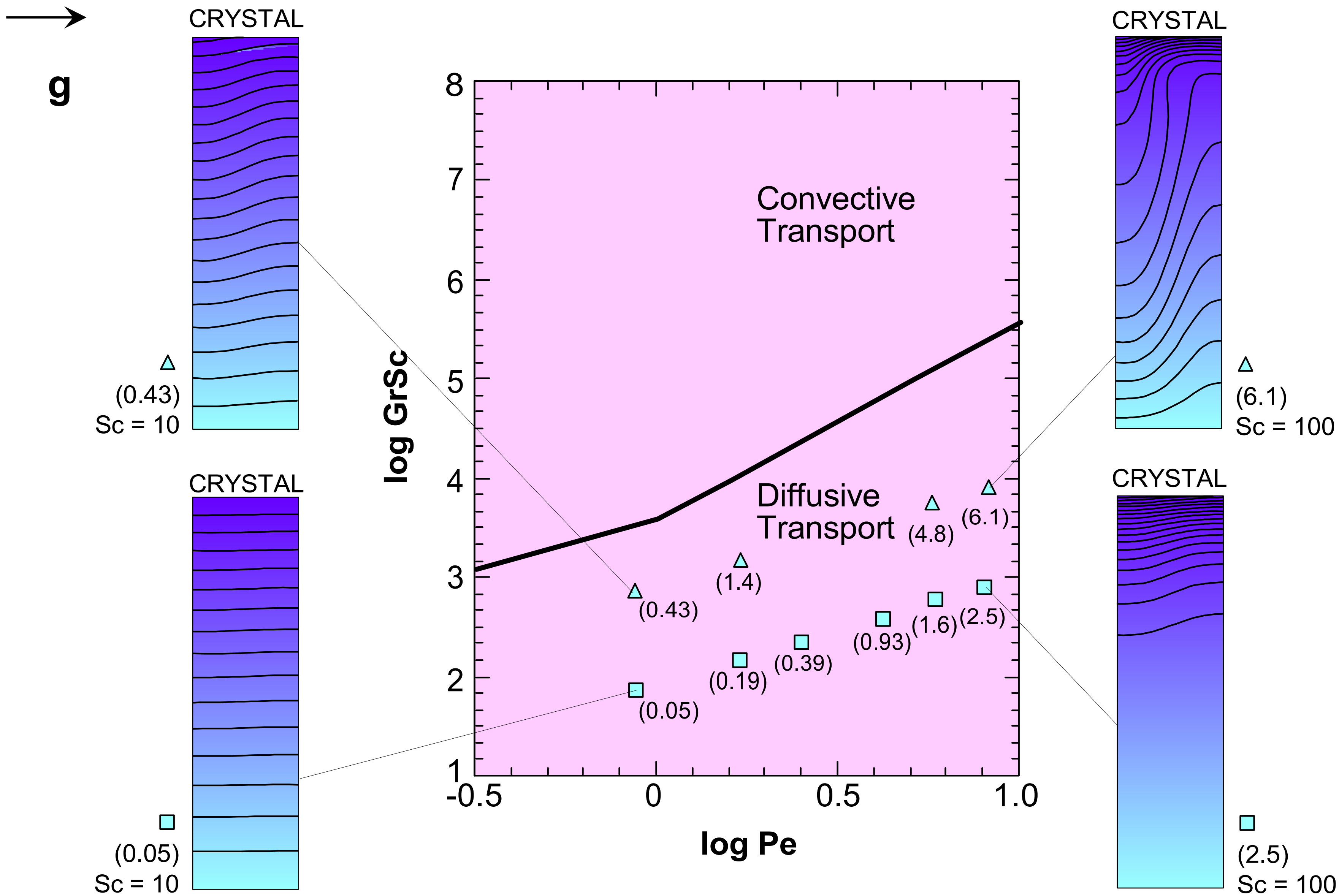
Heat flux through ampoule sidewalls proportional to difference between wall temperature and heater temperature



1 Fixed Furnace
2 Moving Furnace

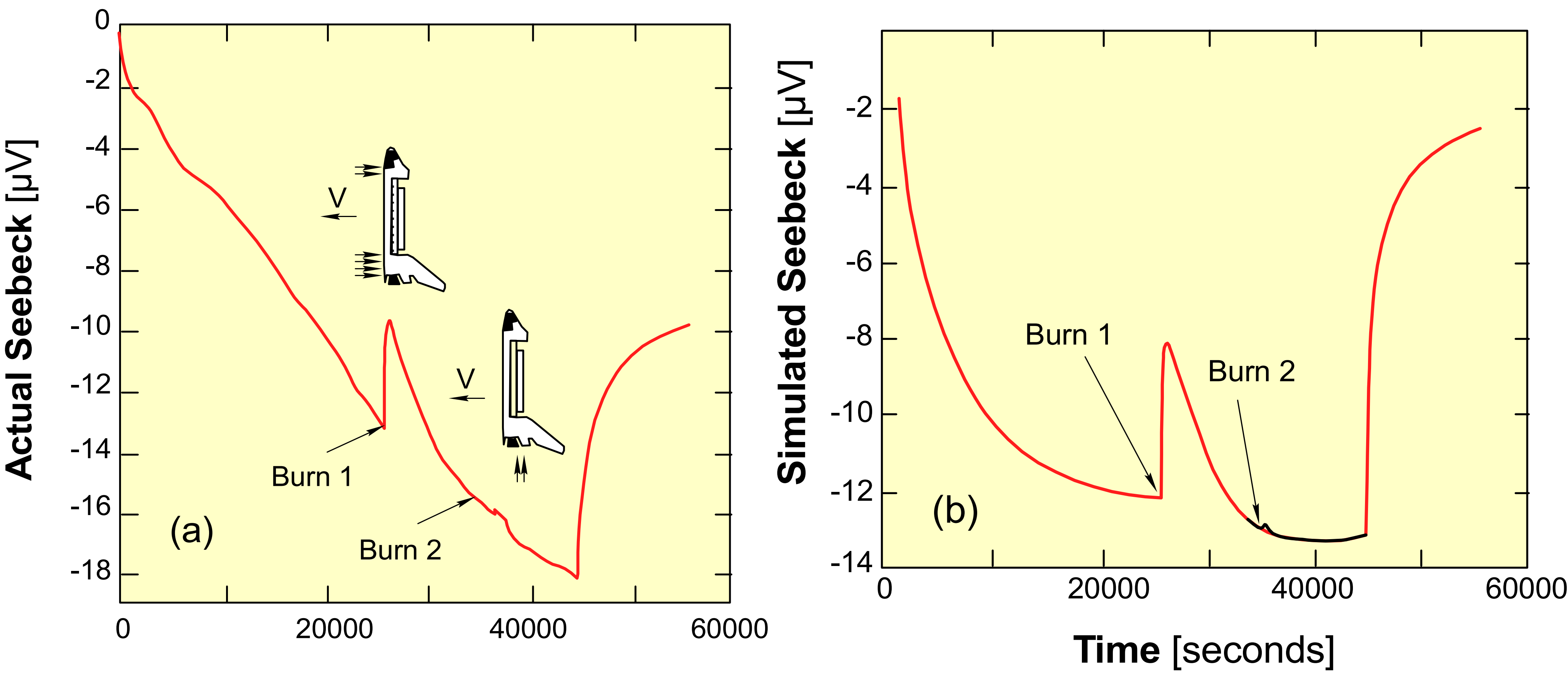
- **Newtonian fluid, linear dependence of density on temperature differentially heated cavity**
- **Two component melt**
- **Ampoule is translated through a furnace at a fixed rate**
- **If convective effects are negligible- lines of equal composition will be parallel to the (flat) crystal melt interface and the longitudinal profile will change exponentially with distance away form the interface**

Steady acceleration: effects on directional solidification



g-jitter effects: The MEPHISTO g-jitter Experiments on USMP-3

Response of solute transport to impulsive g-jitter in a tin-bismuth alloy

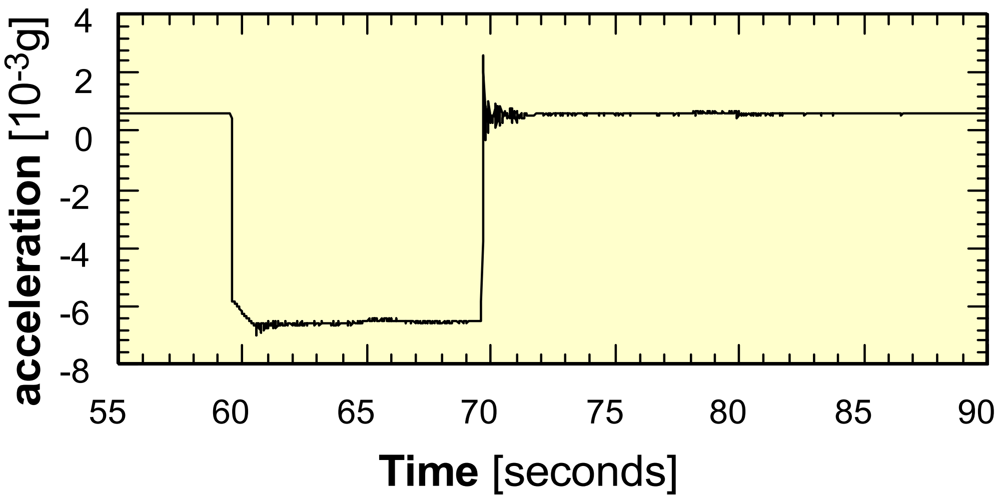


g-jitter effects: The MEPHISTO Experiments on USMP-3

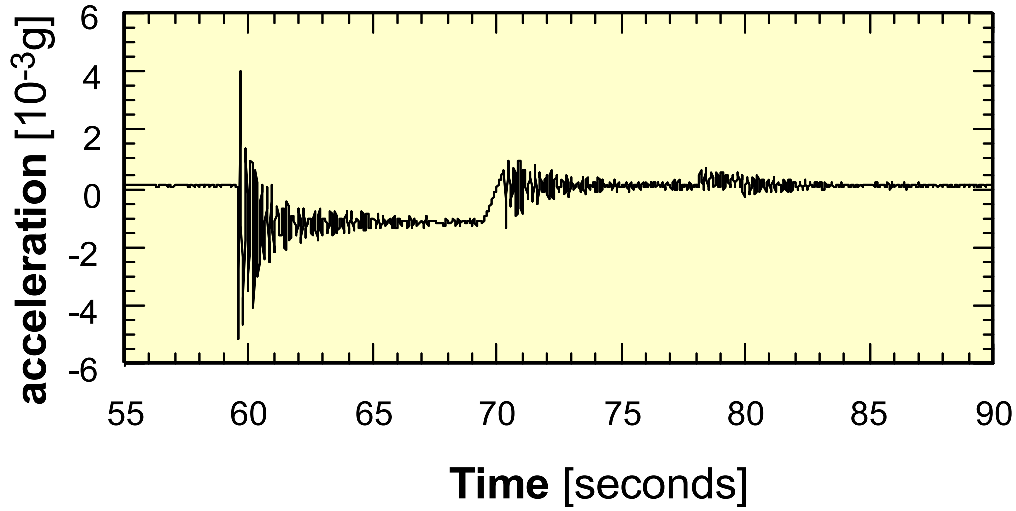
SAMS Acceleration Data

MET: 7/00:25

x-acceleration

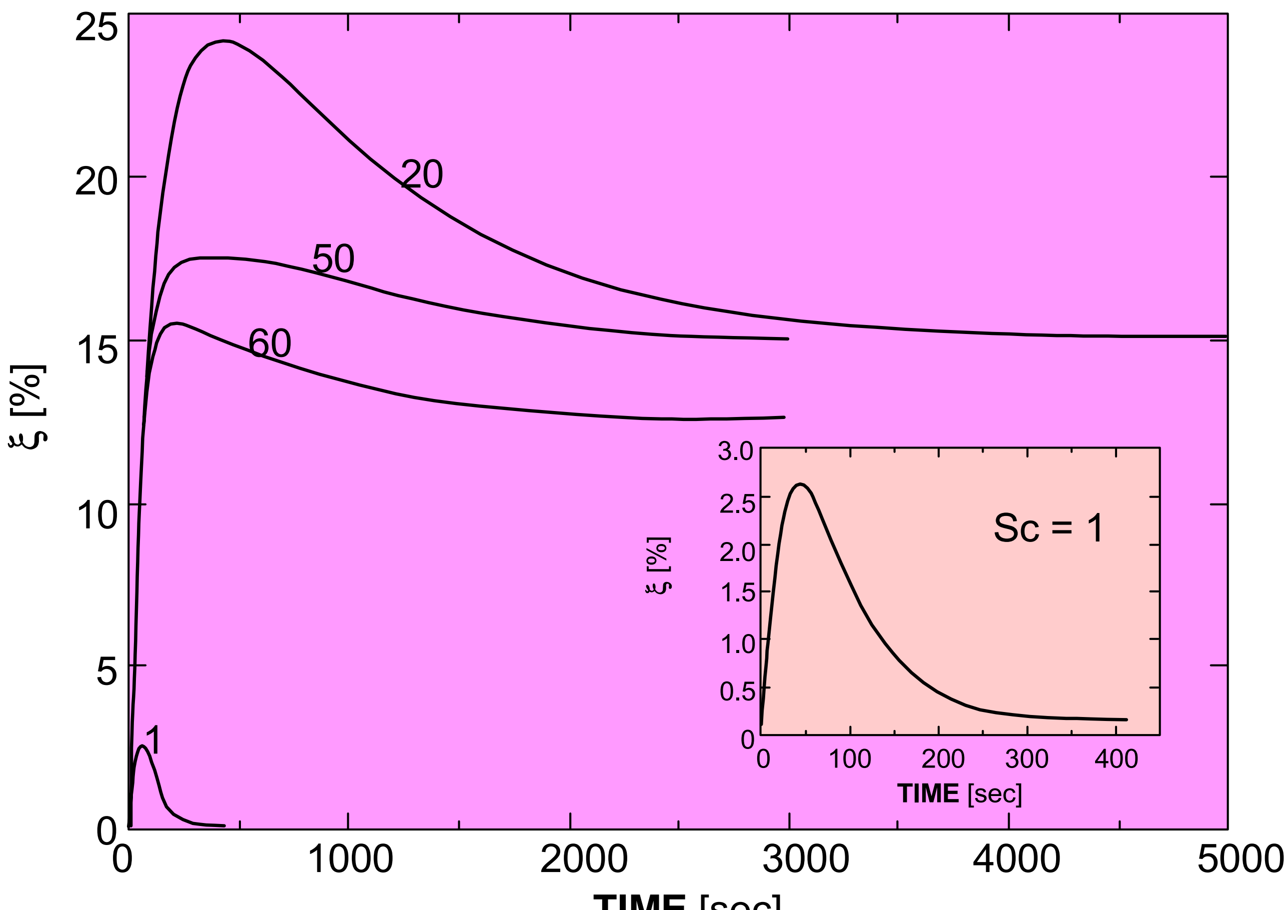


net z+y acceleration



g-jitter effects on directional solidification: periodic acceleration

Interfacial composition nonuniformity as a function of time for a 1 Hz acceleration oriented parallel to the melt-crystal interface



ζ = Interfacial non-uniformity, C_{max} - C_{min} / C_{av}

C = composition

Mean flows generated by periodic g-jitter acceleration

The vibrational Rayleigh number, Rav, is the ratio of the characteristic time for heat transfer by conduction to the characteristic time for convective heat transfer

Insulated top and bottom walls

$$\frac{\partial T}{\partial n} = 0$$

Horizontal vibration

$$\Omega\sqrt{2 Rav \Pr}\cos(\Omega t)$$

$T = 1$

$T = 1$ $T = 0$

$\frac{\partial T}{\partial n} = 0$ $\frac{\partial T}{\partial n} = 0$

$$\frac{\partial T}{\partial n} = 0$$

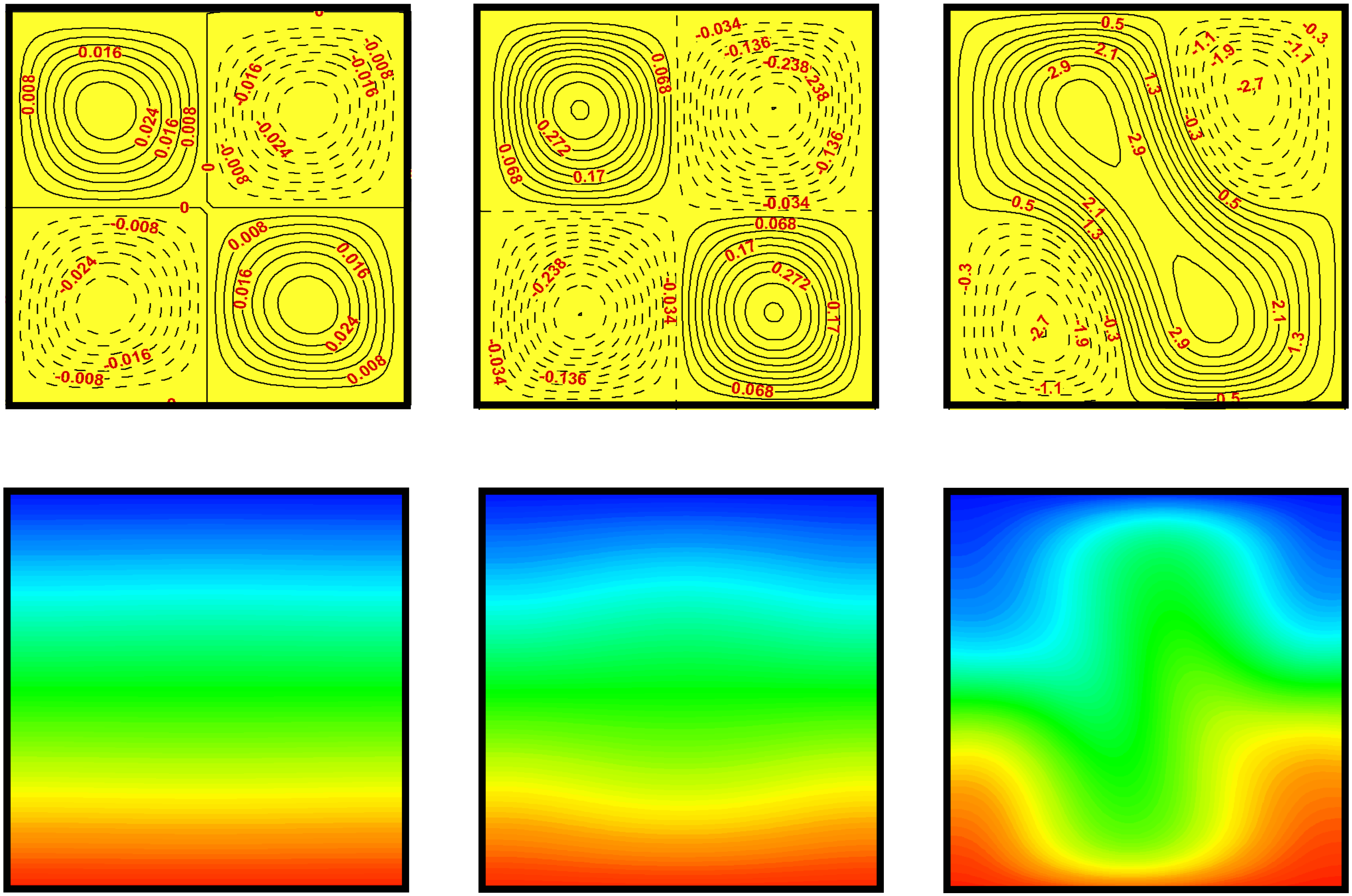
No steady acceleration *Ra* = 0

$T = 0$

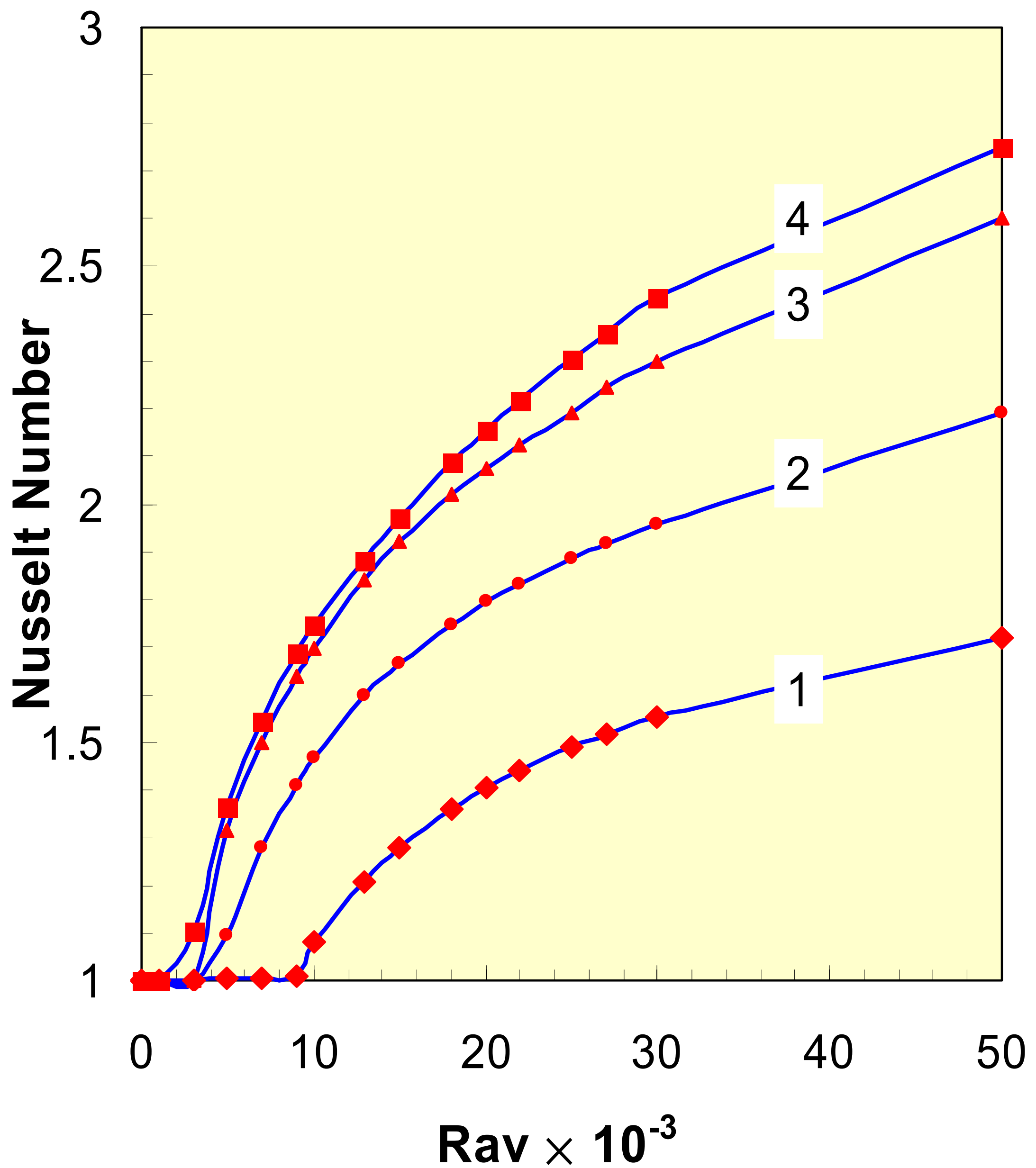
flow

Mean flows and temperature profiles generated by periodic g-jitter acceleration

$Rav = 10^3$ $Rav = 10^4$ $Rav = 10^5$

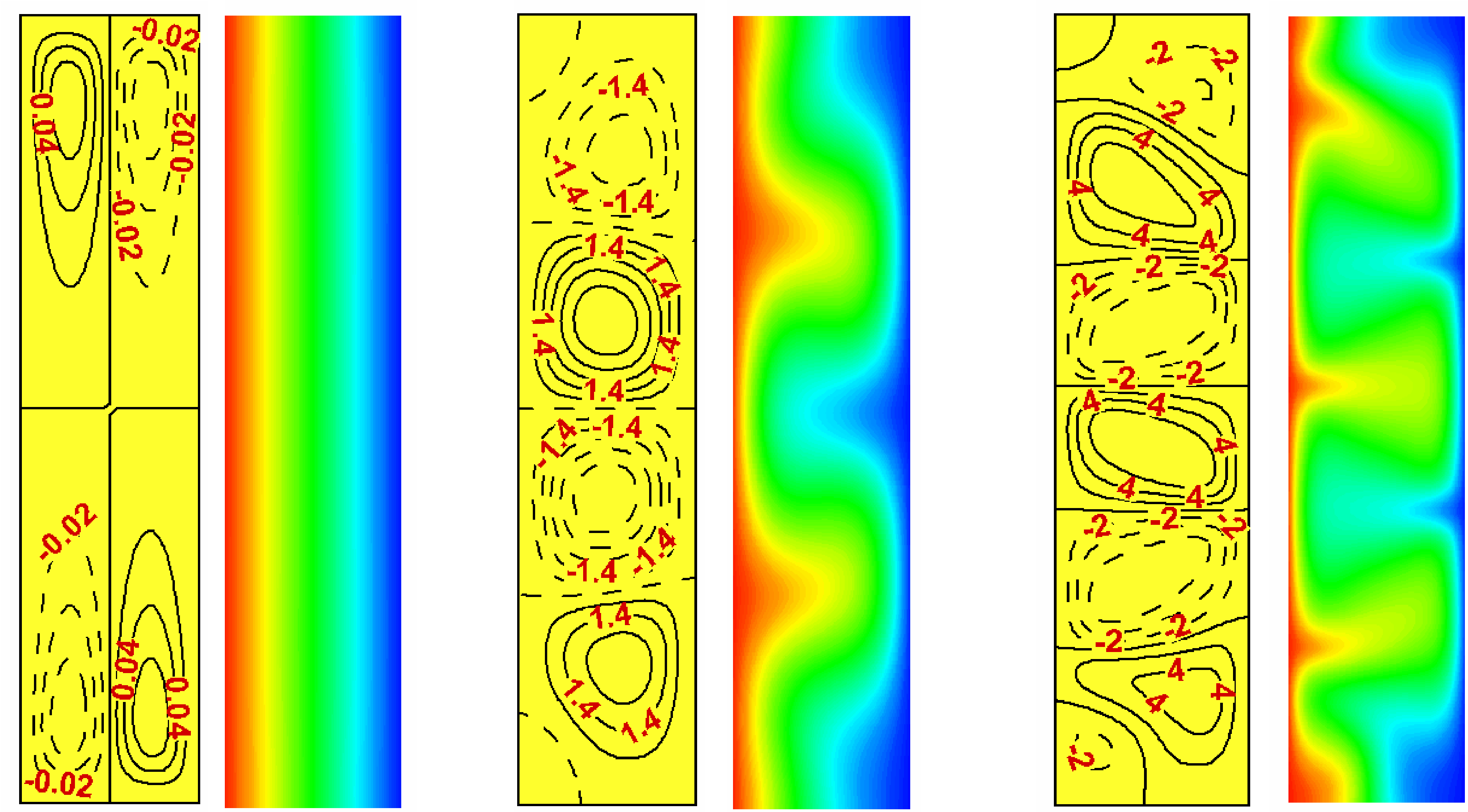


Dependence of heat transfer on Rav and Aspect Ratio



Aspect Ratio = h/w

Effect of cavity Geometry and Rav



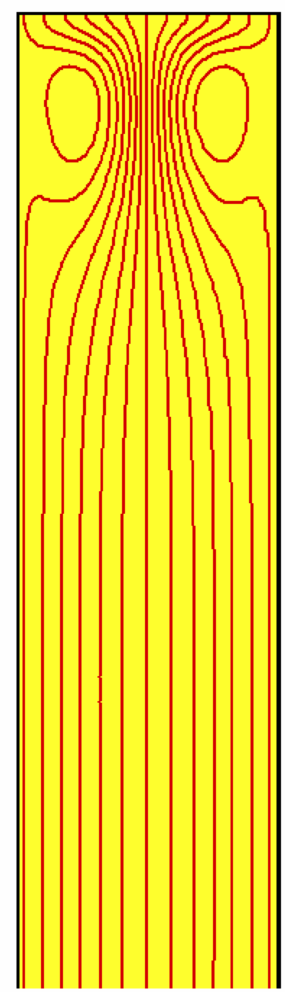
Rav = 1500 *Rav* = 10^4 *Rav* = 10^5

Mean Transport due to g-jitter during Directional Solidification

Ra = 11
Rav = 500
Pr =0.153 (Sn-Bi)
Ω= 2000

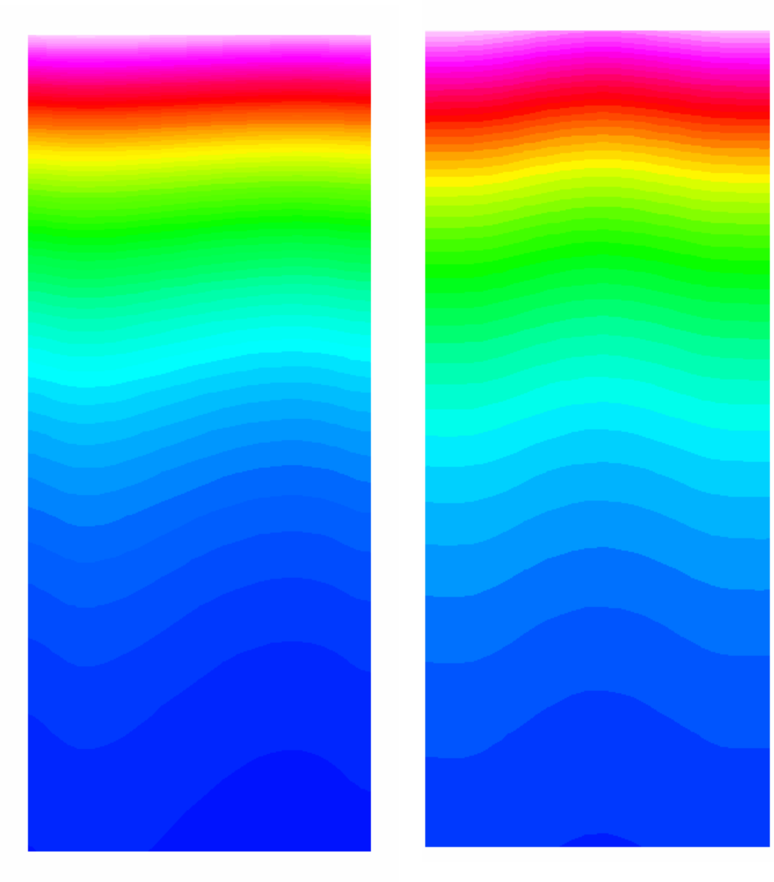
Vibration parallel
to the crystal-melt
interface

3.38 Hz



Ra = 11

Mean Transport due to g-jitter during Directional Solidification



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Ra = 11

Vibration parallel to the crystal-melt interface

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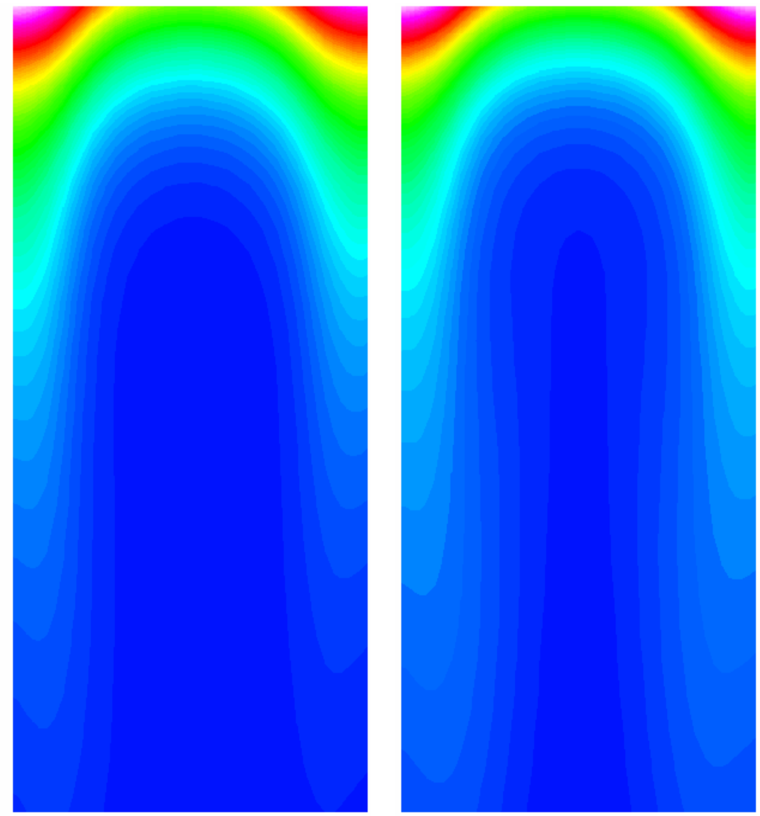
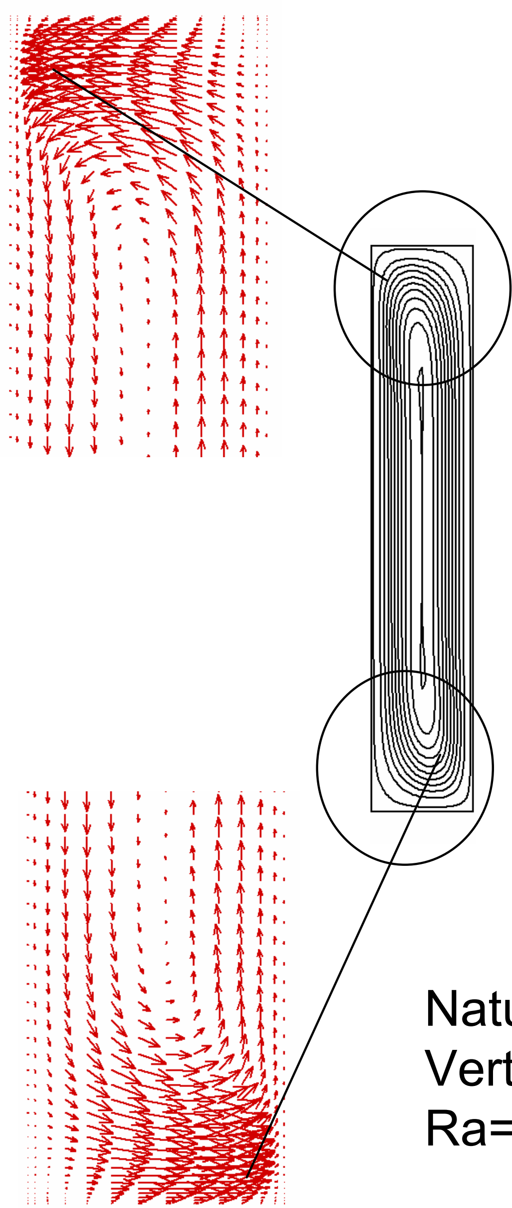
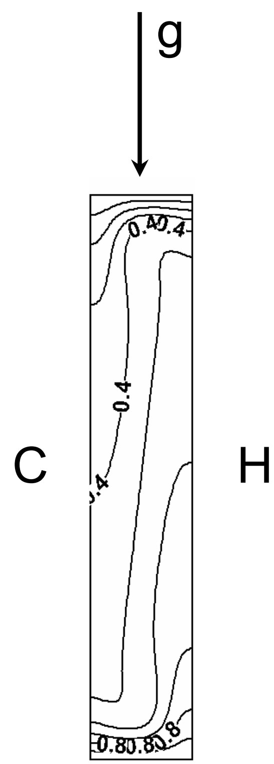


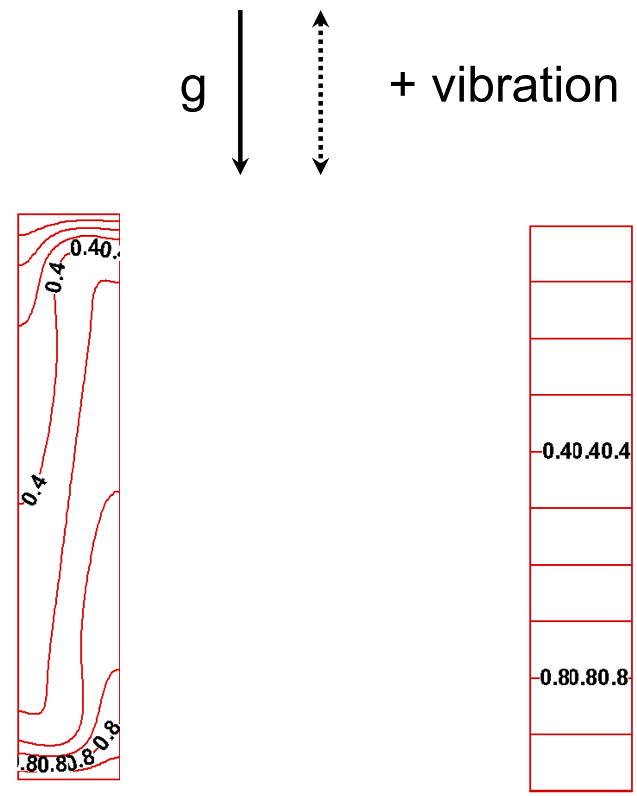
Ra = 11
Rav = 10^4
Pr =0.153 (Sn-Bi)
Ω= 2000

Flow Suppression by vibrational flow





Natural convection
Vertical temperature gradient
Ra=10^4, Pr = 6.96 (water)

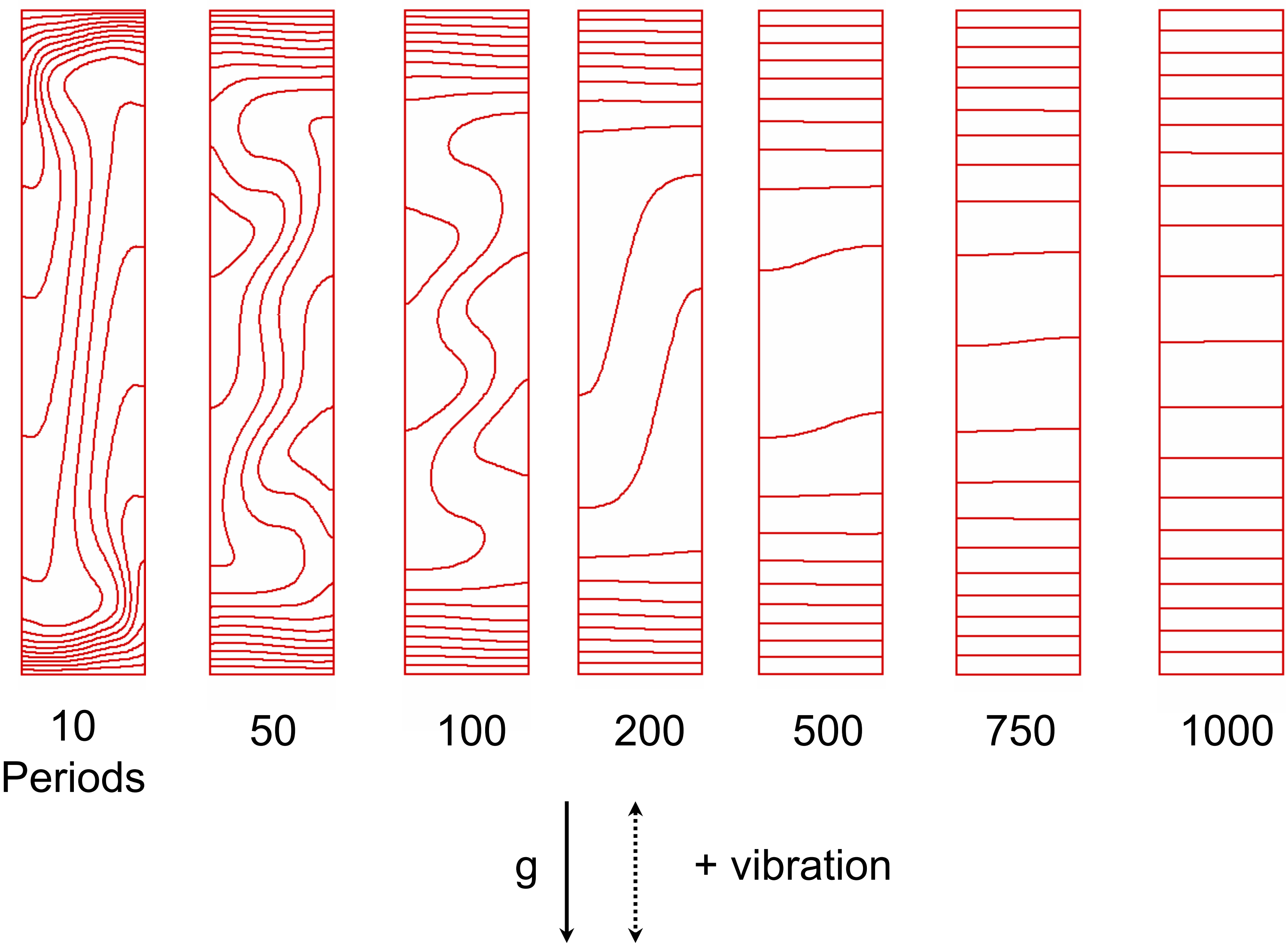


Rav = 10^4
Ω = 8000

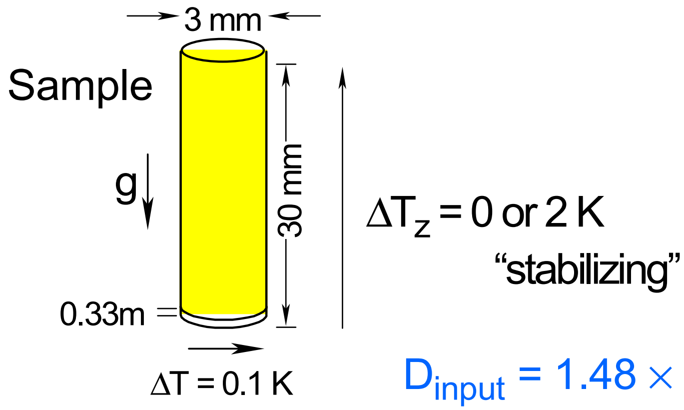
Rav = 10^5
Ω = 2×10^4

Flow Suppression by vibrational flow

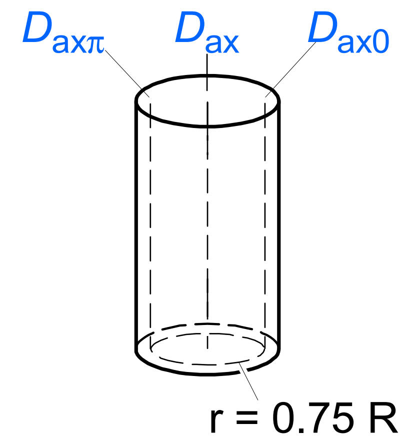
$Rav = 10^5$
$\Omega = 2\text{x}10^4$



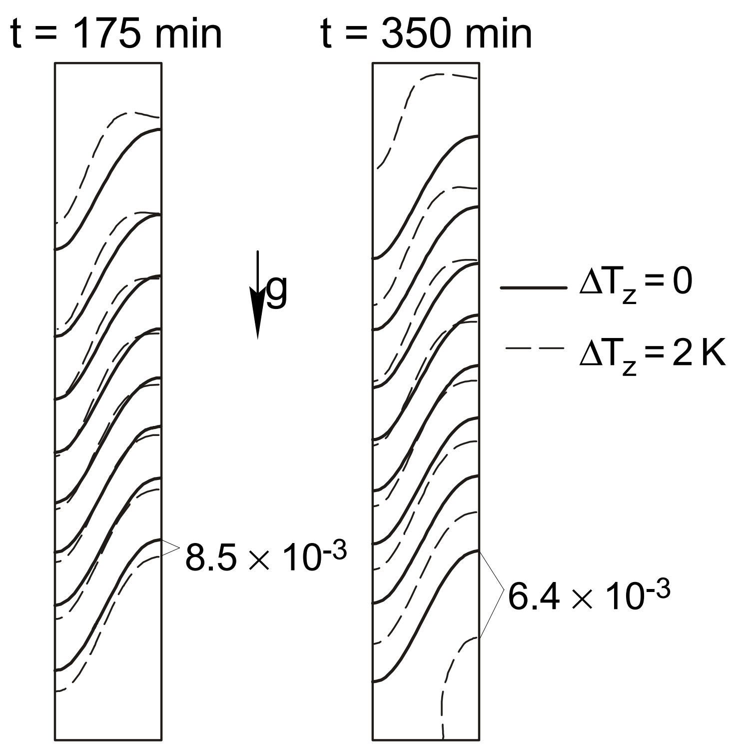
Contamination of diffusion measurements by convection

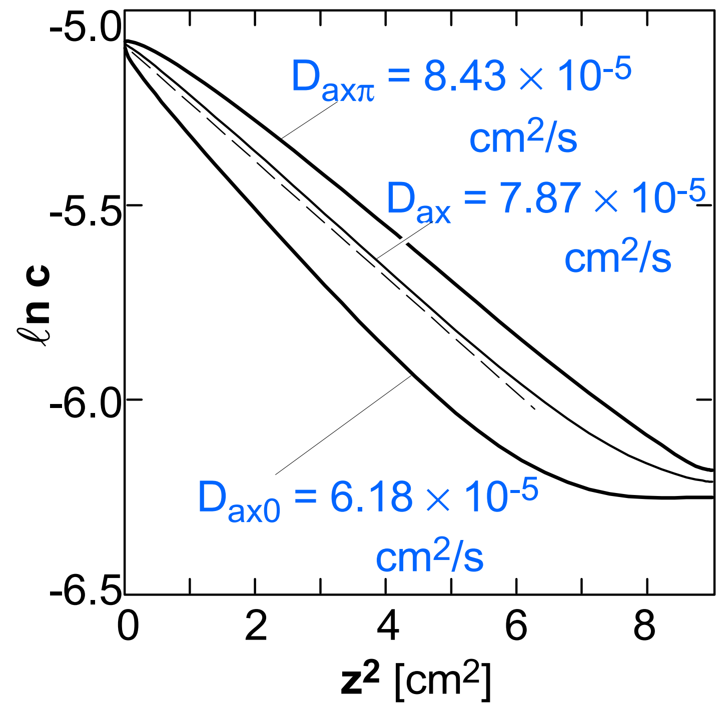


$D_{input} = 1.48 \times 10^{-5}$ cm²/s



Ra = 3
Pr = 10^{-2}



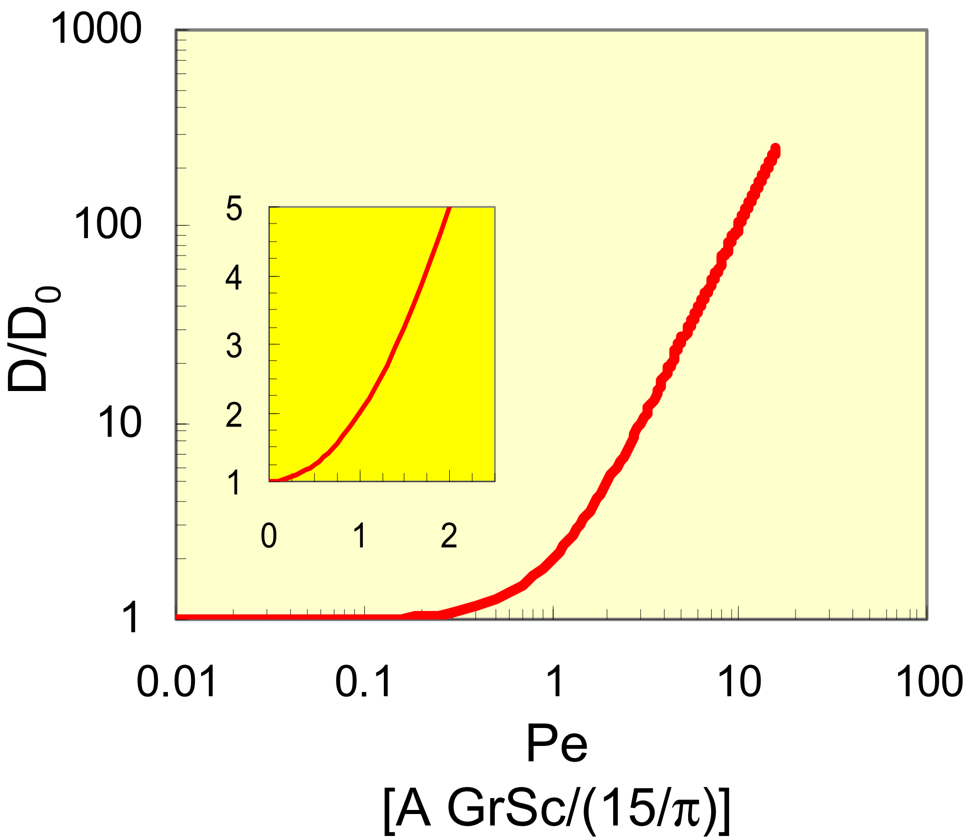


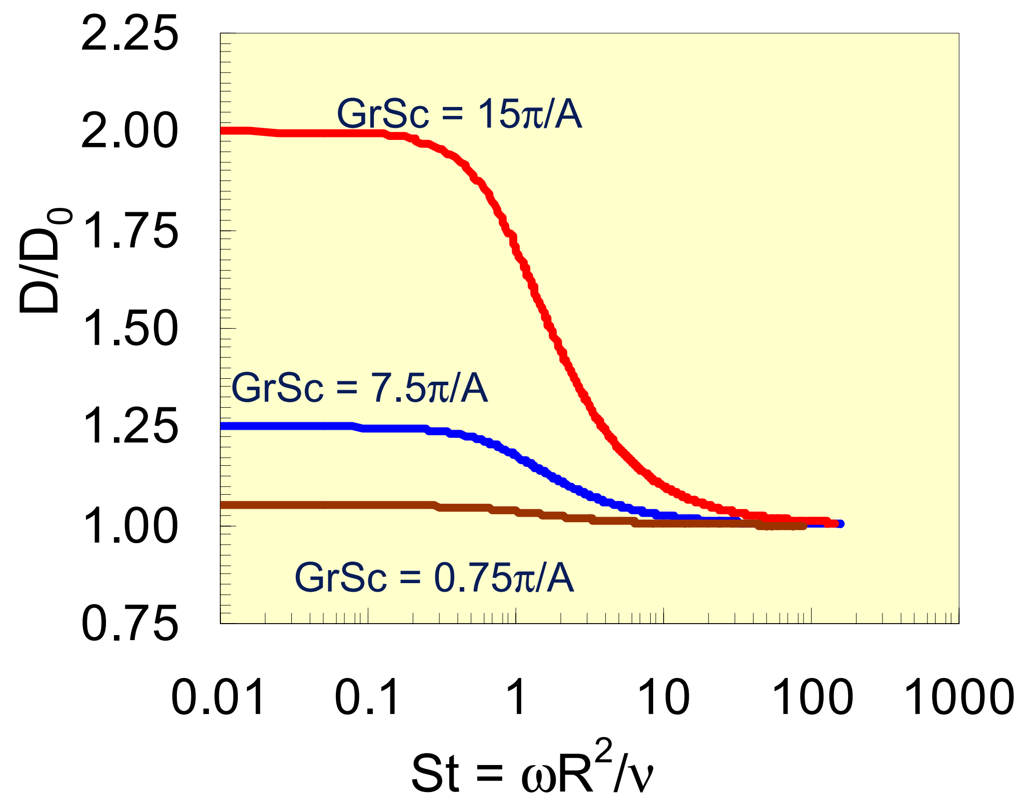
C = concentration

Gravity effects on diffusive processes

Ratio of measured diffusion coefficient D to actual coefficient depends on the ratio of the characteristic time for diffusive transport to the characteristic time for convective transport- GrSc, the aspect ratio, A of the container, and the dimensionless frequency St which is the ratio of the viscous response time to the period of the g-jitter.

$$\frac{D}{D_0} = 1 + \left(\frac{A}{15\pi}\right)\frac{(GrSc)^2}{(1+St^2)}$$





Summary

- Significant progress has been made toward the understanding of g-jitter effects on microgravity experiments
- Most of this understanding is based on theory and simulation
- Recent work on mean flows driven by oscillatory g-jitter shows that even if the time-dependent response of the fluid is small in amplitude, a mean flow may still be generated that can lead to significant compositional distortion.
- Convection driven by compositional gradients may be more sensitive to oscillatory g-jitter at high frequencies. More work is needed to clarify this
- More experimental evidence of on-orbit g-jitter effects would be useful
- Free surfaces and fluid interfaces are particularly sensitive to changes in gravitational environment. Liquid configurations generally take on very different characteristics in weightlessness
- Gas-liquid and two –phase flows have very different flow regime characteristics under 1-g as compared to zero-g or partial-g. This needs to be better understood
- Lack of effective buoyant transport can lead to problems with bubble accumulation