Mixing transition in time-dependent flows

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We have developed a procedure to determine when the interfaces become turbulent

We address two fundamental questions:

(1) When do the interfaces in a instability-driven flow become turbulent ?

(2) Have existing experiments achieved turbulent state ?

Rocket-Rig (AWE), Linear Electric Motor (LLNL), Laser-Driven (Omega), shock tube (Univ. of Arizona), Gas Curtain (LANL), classical RT experiments (Cambridge Univ. and All Union Sci. Res. Inst. Exp. Phys.)

This procedure provides much needed guidance for future designs of both classical fluid dynamics and laser-driven turbulent mixing experiments

Both spatial and *temporal* scales must be reached for achieving mixing transition

Physics

- The greatest differences in flow behavior occur before and after this critical mixing transition time

- If turbulent mixing of materials is important, then future experiments must reach the relevant Reynolds number

- Both relevant spatial and temporal scales must be achieved

Design of future experiments

- Provide the necessary condition for experimental facilities and target design

Important length scales of turbulent flow are defined by the classical Kolmogorov theory

- **The outer scale of the flow δ is determined by external forcing**
- **The Kolmogorov length scale η is the smallest length scale**

Inertial subrange

- **The existence of turbulent flow is indicated by the inertial subrange**

$$\eta << \lambda << \delta$$

The dynamics at an inertial subrange λ is not affected by δ and η.

- **This condition is usually too broad to be of practical use.**

Cascade picture illustrates many aspects of the Kolmogorov phenomenology

Outer-scale δ

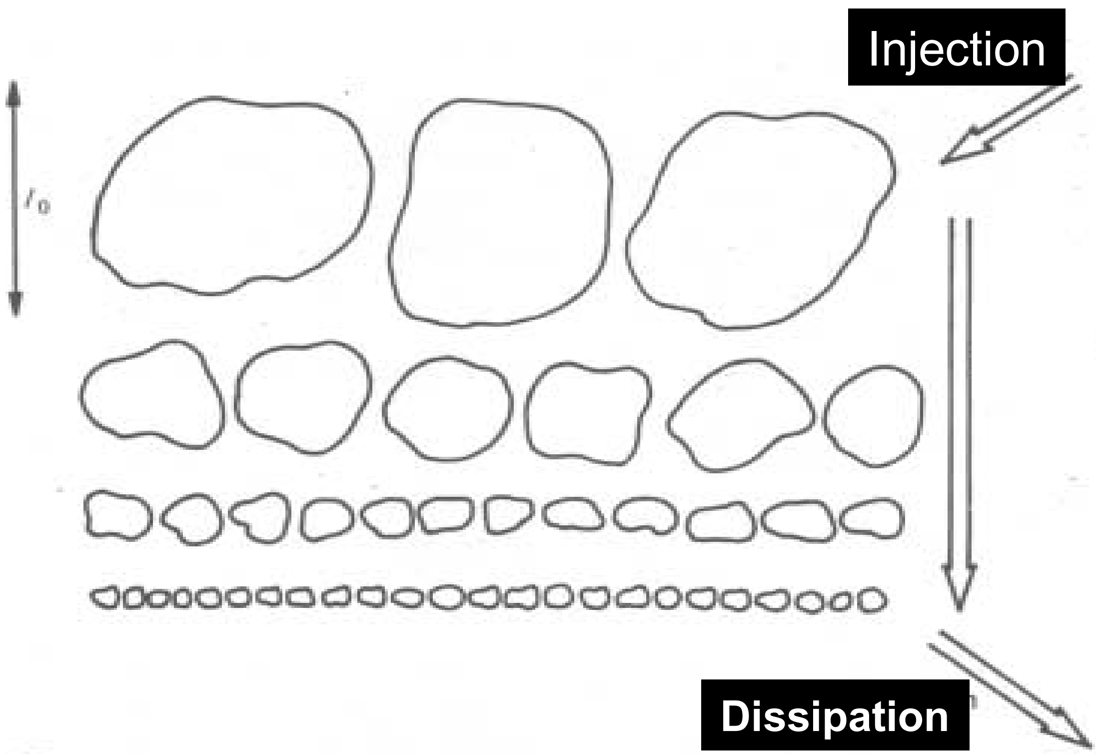


FIGURE 1. The energy cascade according to the 1941 Kolmogorov theory. Notice that at each step the eddies are space filling.

Inertial range ?

Kolmogorov scale η

Review: Zhou and Speziale, Appl. Mech. Rev., 1998

Measured energy spectrum of fluid turbulence follows the Kolmogorov –5/3 scaling

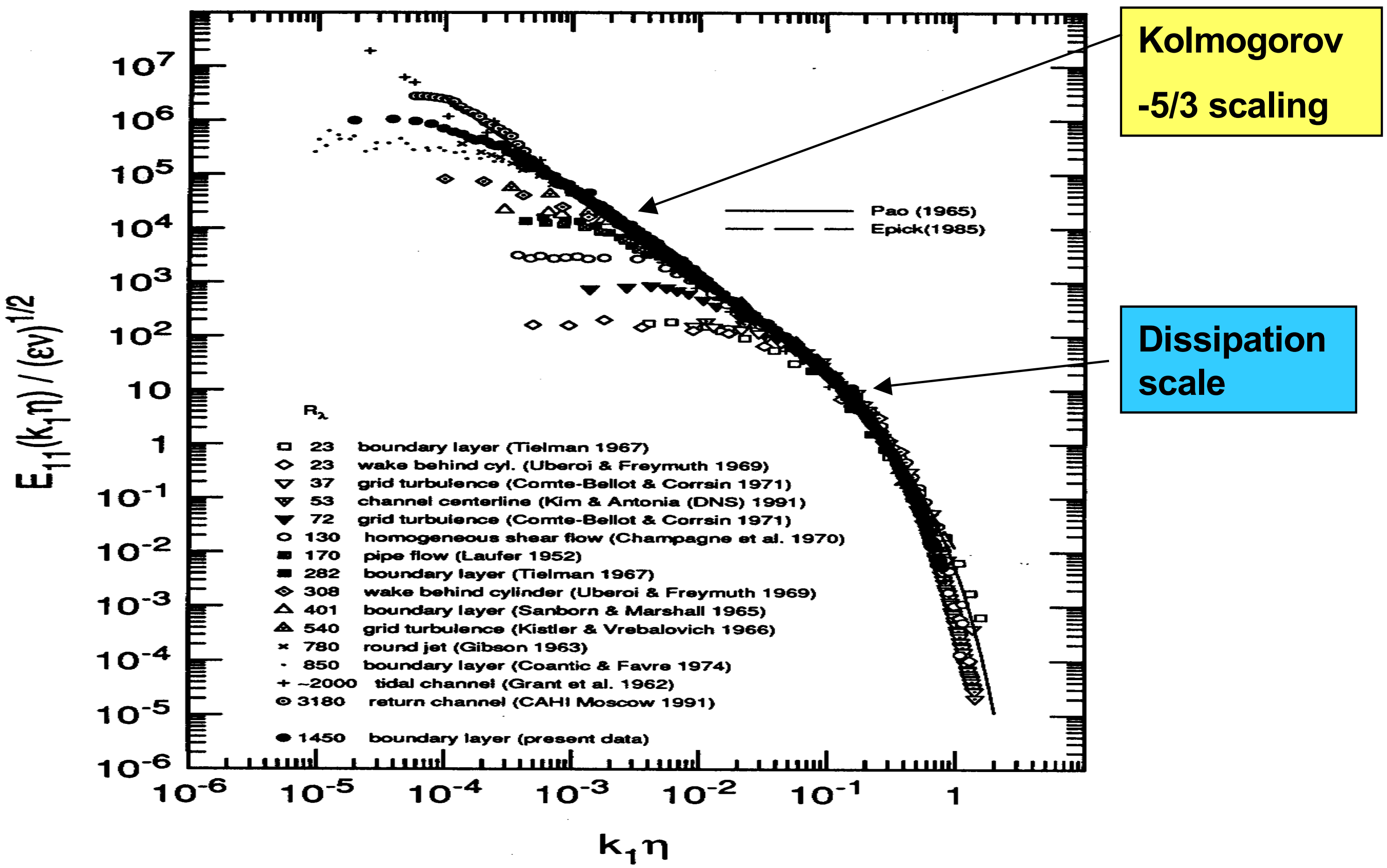


FIGURE 11. Normalized longitudinal spectrum compared with data from other experiments. This compilation is from Chapman (1979) with later additions.

Mixing transition of Dimotakis refines the criterion for transition to fully developed turbulence

The mixing transition

- Reflects the inability of the flow to remain stable as the damping effects of viscosity are reduced with increasing Reynolds number

$$\mathrm{Re} = \frac{VL}{\nu}$$

- Visualization illustrates that the transition is rather abrupt and results in an increasingly disorganized three-dimensionality.

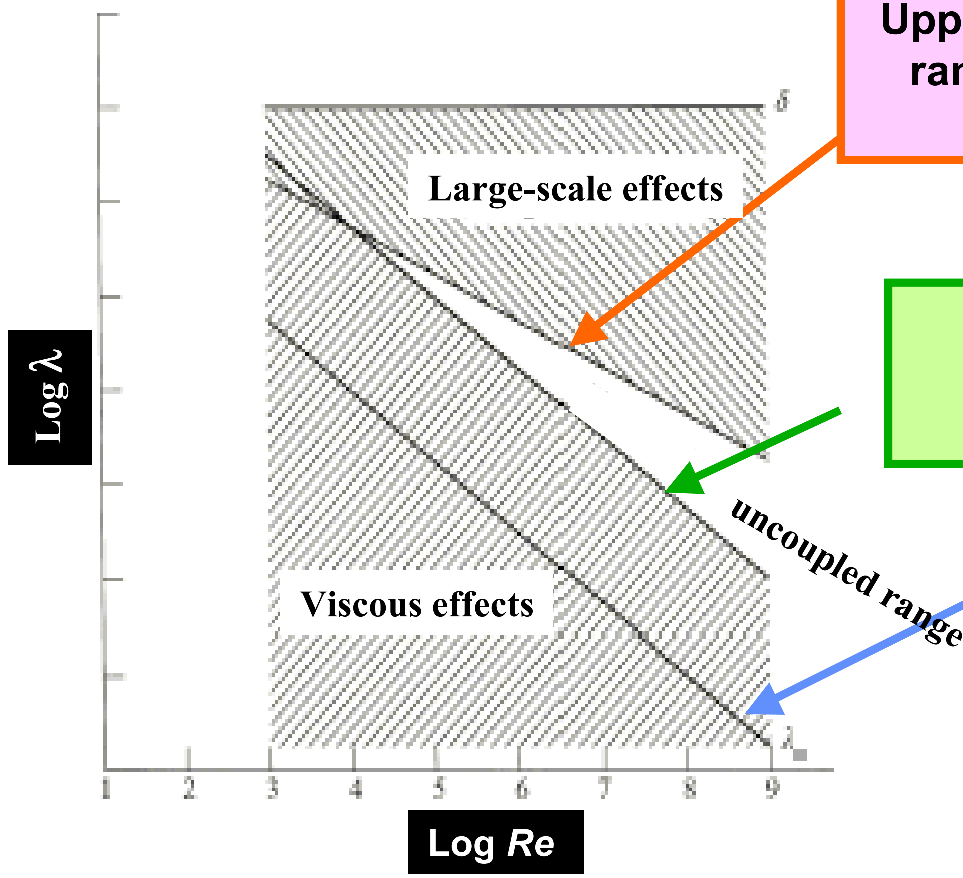
- To fix a tighter bound, Dimotakis proposed that the extent of the inertial range can be narrowed to

$$\eta \ll \lambda_\nu \ll \lambda \ll \lambda_L \ll \delta$$

λ_ν is the inner viscous scale, λ_L is the Liepmann-Taylor scale

P.E. Dimotakis, *JFM* 409, 69 (2000)

This transition is co-incident with the appearance of a range of scales decoupled from both large-scale and viscous effects



Upper bound of the inertial range: Liepmann-Taylor scale

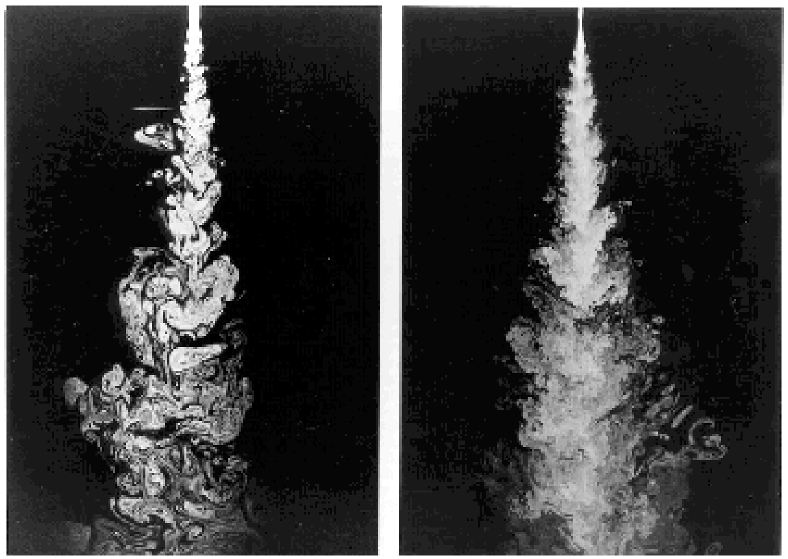
Lower bound of the inertial range: Inner viscous scale

The smallest length scale: Kolmogorov scale,

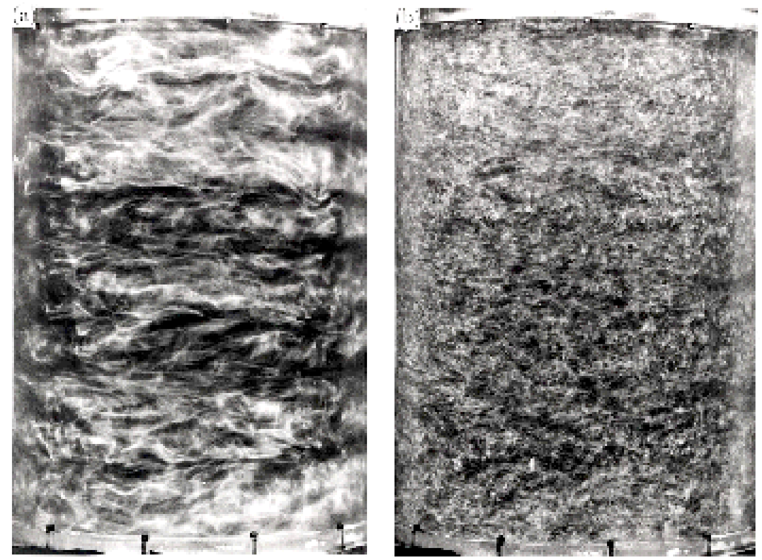
Figure 19. Reynolds number dependence of spatial scales for a turbulent jet

P.E. Dimotakis, *JFM* 409, 69 (2000)

A universal transition to fully developed turbulent mixing was postulated for an outer Reynolds number



Liquid-jet concentration in a round turbulent jet (Dimotakis 1983)

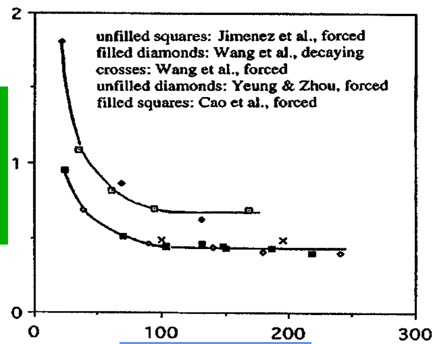


Couette-Taylor flow (Lathrop 1992)

Outer-scale Reynolds number $\geq$ 1-- 2 $\bullet 10^4$ is required

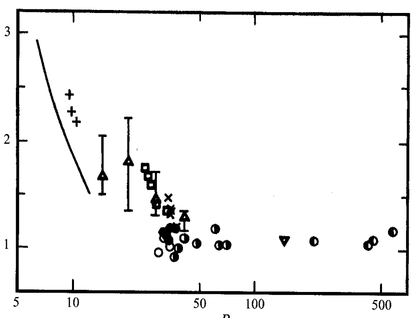
A critical Reynolds number can be found at which a rather abrupt transition to a well mixed state occurs

Dissipation Rate (DNS)

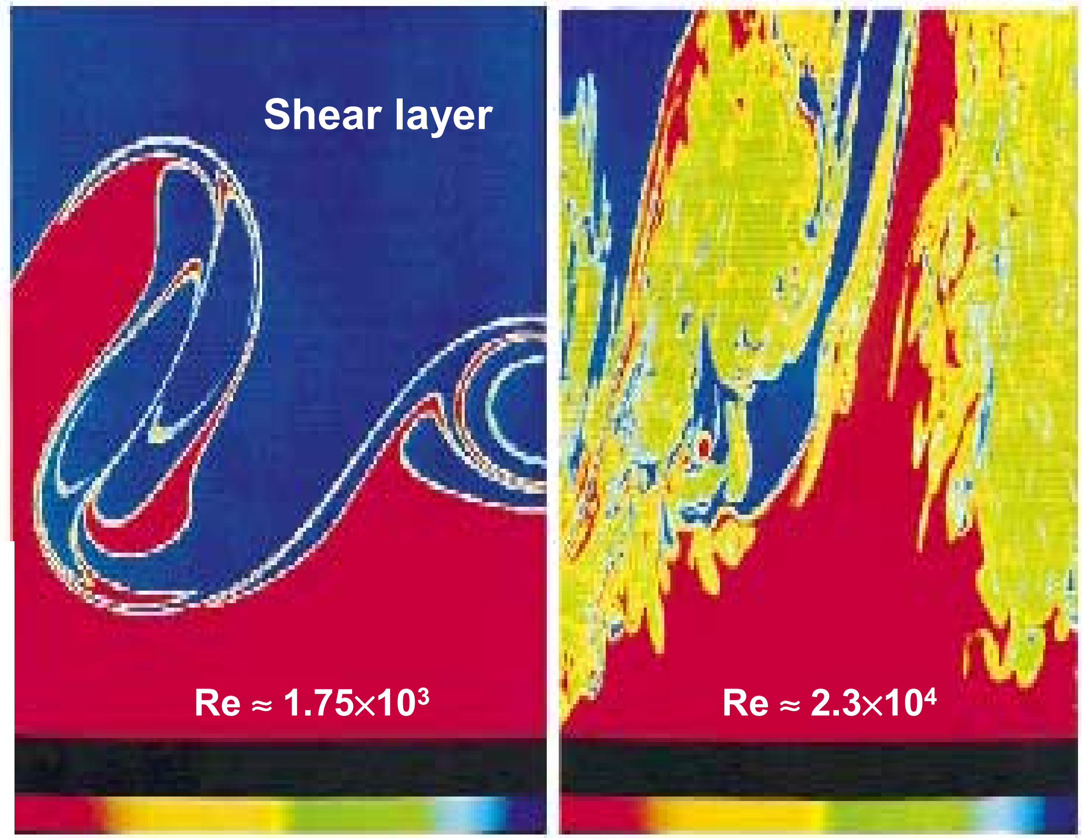


$R_\lambda \approx \mathrm{Re}^{1/2}$

Dissipation Rate **(Experiment)**



$R_\lambda \approx \mathrm{Re}^{1/2}$



The mixing transition at Re ≈ 2 × 10^4 is observed to occur in a wide range of flows

We have extended the mixing transition concept from the stationary to transitional flows

The outer scale is a function of time

- **The outer scale Reynolds number is time dependent**

The Liepmann-Taylor scale

$$\lambda_L = 5\delta\,\mathrm{Re}^{-1/2}$$

is the asymptotic temporal limit of a diffusion layer

$$\lambda_d(t) = 4 \bullet (\nu t)^{1/2}$$

- **The inner viscous length is a function of time --** $\lambda_\nu(t) = 50 \bullet h\,\mathrm{Re}^{-3/4}$

Criteria for mixing transition in time-dependent flows:

$$\lambda_\nu(t) << \lambda << Min\,[\lambda_L(t), \lambda_d(t)]$$

RT and RM instability induced turbulent flow can be determined by the outer-scale length scale and Re

- The mixing zone width (*h*) is the only relevant length scale for Rayleigh-Taylor and Richtmyer-Meshkov instability driven flows
- The outer-scale length scale δ is identified as *h*.

The mixing zone widths of both RT and RM driven flows are functions of time:

RT: $h = \alpha A g t^2$ **with** $\alpha = \alpha_b + \alpha_S$ **, A=** $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$

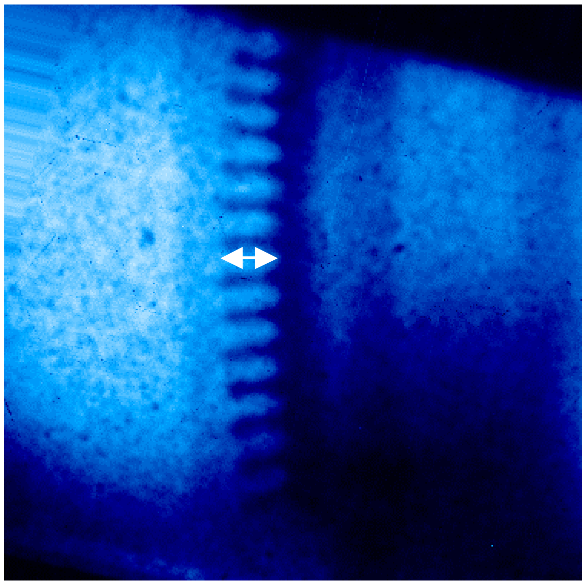
RM: $h \sim t^{\theta}$ **with** θ **= 0.2 -- 0.6**

Reynolds number: **Re =** $\dfrac{h \bullet V}{\nu} = \dfrac{h \bullet \dot{h}}{\nu}$

- **Liepmann-Taylor scale:** $\lambda_L = 5h \bullet \mathrm{Re}^{-1/2}$
- **Inner viscous scale:** $\lambda_\nu = 50 \bullet h\, \mathrm{Re}^{-3/4}$

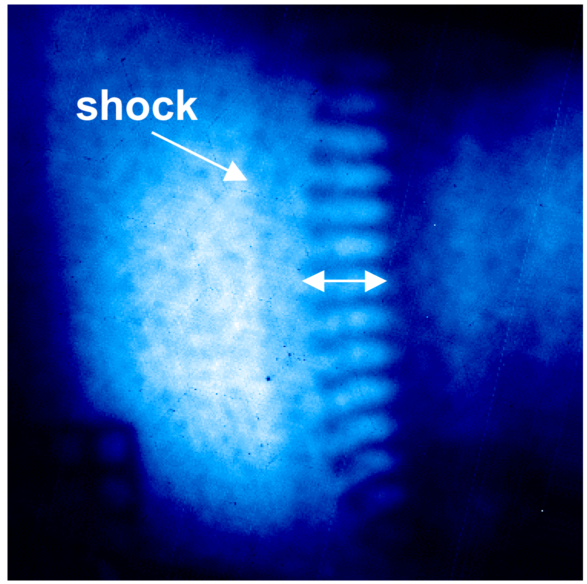
Coefficients from Dimotakis, *JFM* 409, 69 (2000)

The evolution of a 2D single-mode perturbation (λ=50µm, a_0=2.5µm) is observed with x-ray radiography



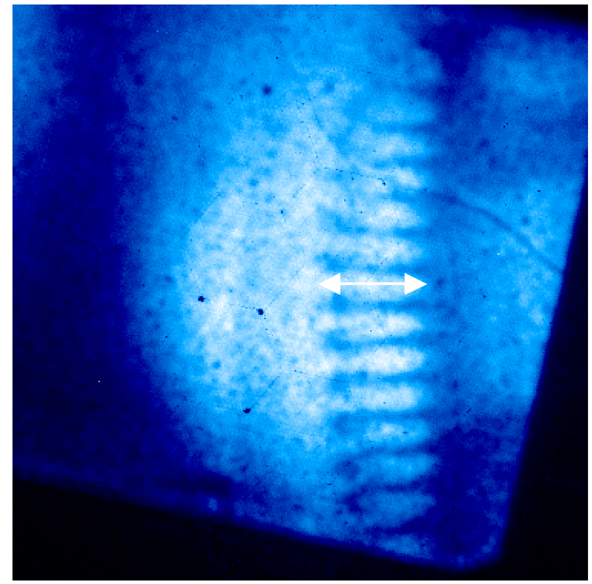
t = 8 ns

$a_{P\text{-}V}$ = 83 µm



t = 12 ns

$a_{P\text{-}V}$ = 121 µm

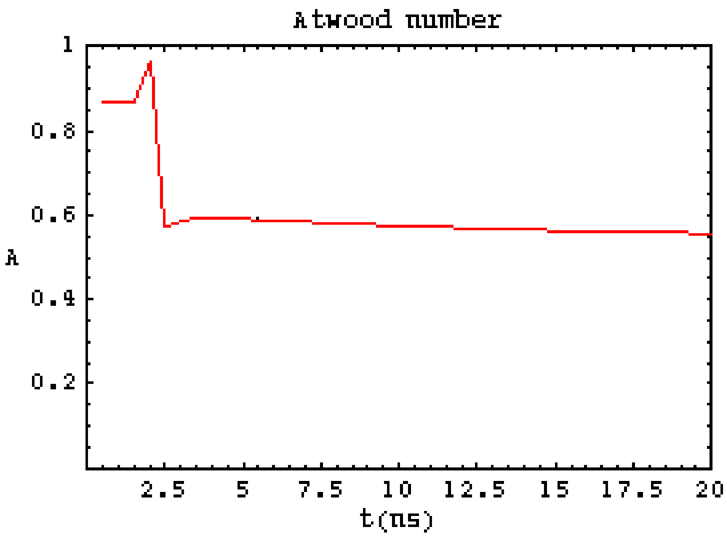


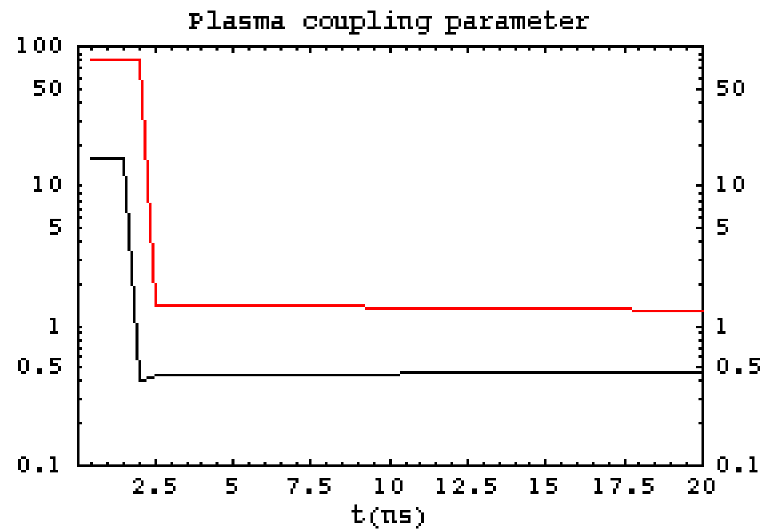
t = 14 ns

$a_{P\text{-}V}$ = 157 µm

Radiographic images obtained with 4.7keV Ti He-α x-rays imaged onto a gated x-ray framing camera

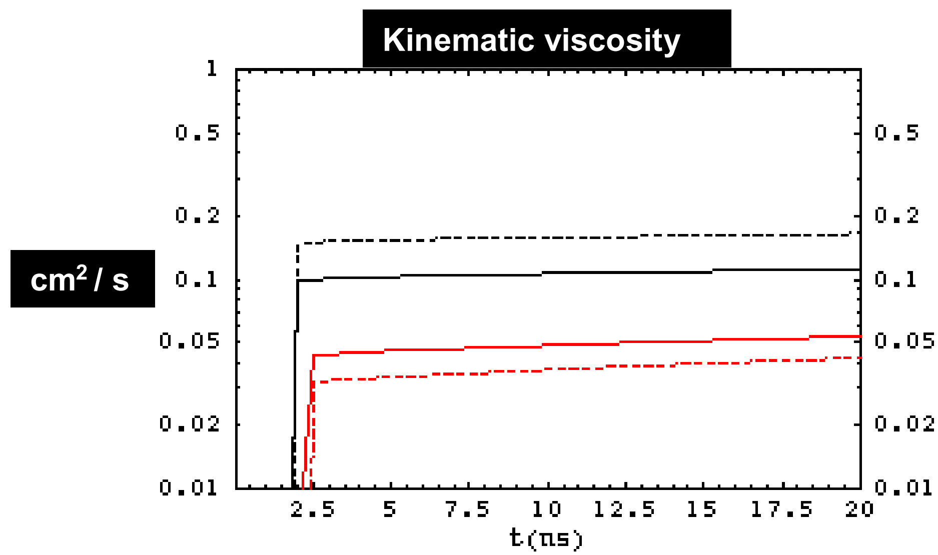
Parameters characterize the high temperature, elevated Reynolds number flow





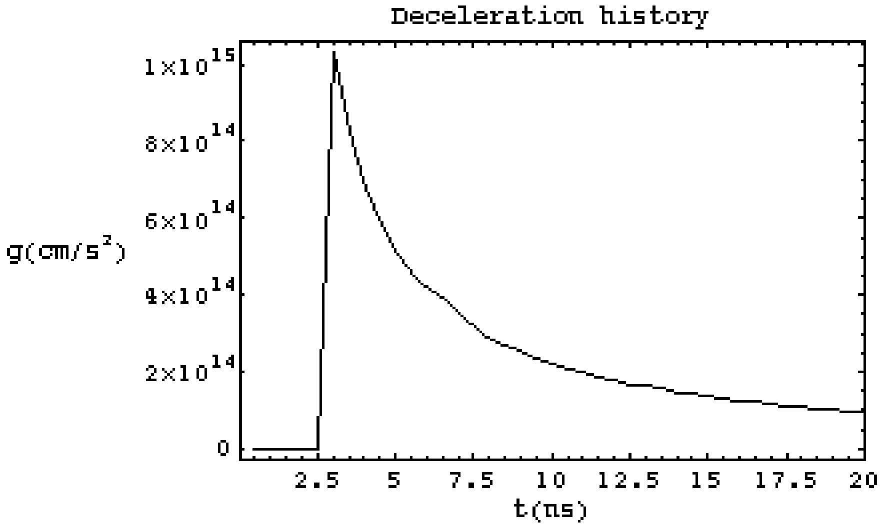
The kinematic viscosity is computed using the formulation for dense plasma mixtures

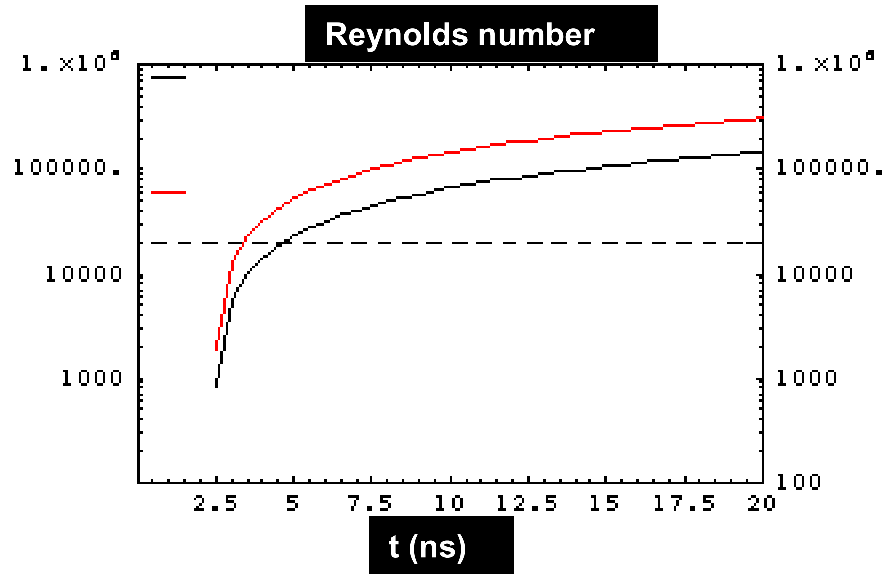
Clerouin et al., *Europhysics Lett.* Vol. 42, p37 (1998)

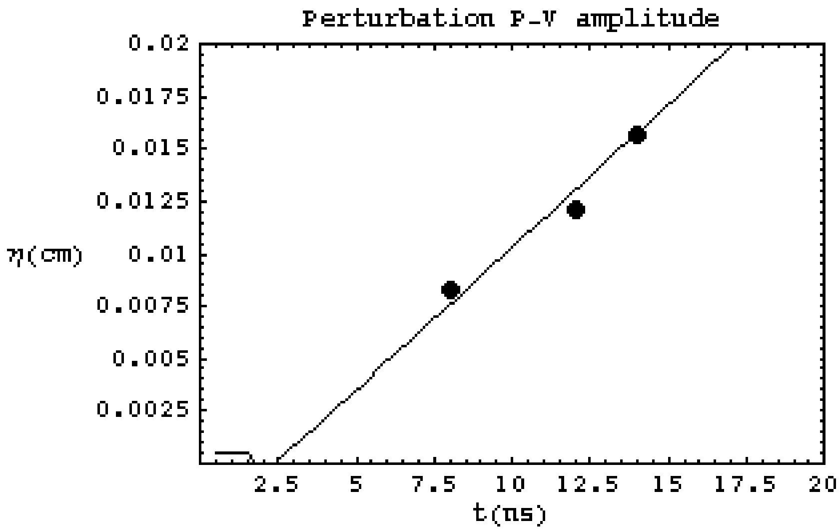


YZ_IWPCTM_113001-14

Mixing transition predicted using the mixing zone width and outer-scale Reynolds number (Dimotakis)



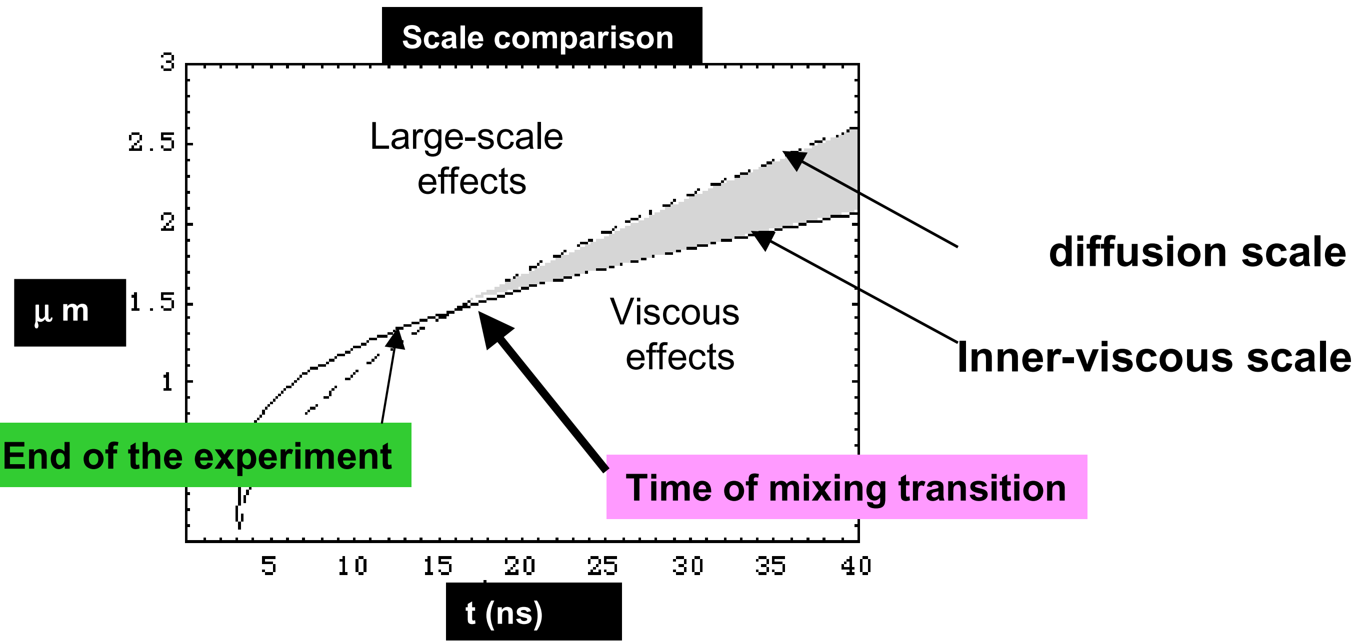




The Reynolds number can be sufficiently greater than the mixing transition threshold of Dimotakis (i.e. Re>>2 x 10^4), yet the flow has obviously not transitioned.

Caveat: single mode

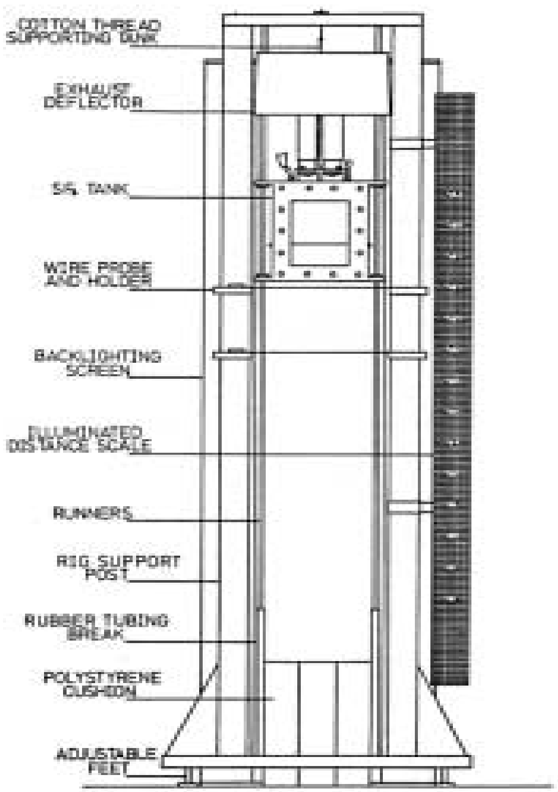
The experiment was terminated before reaching the time required for achieving the mixing transition

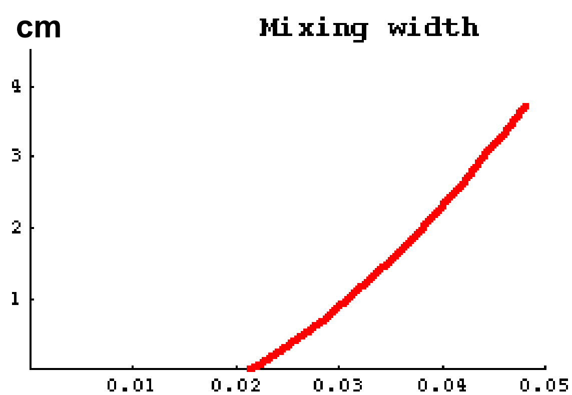


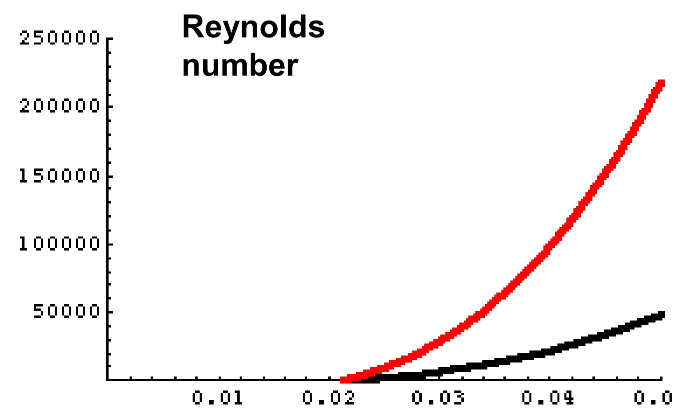
Guided by this type of analysis, new laser-driven experiments are being designed for accelerating the mixing transition process:

- **Longer duration of experiment**
- **Multi-mode initial conditions**
- **3D initial conditions**

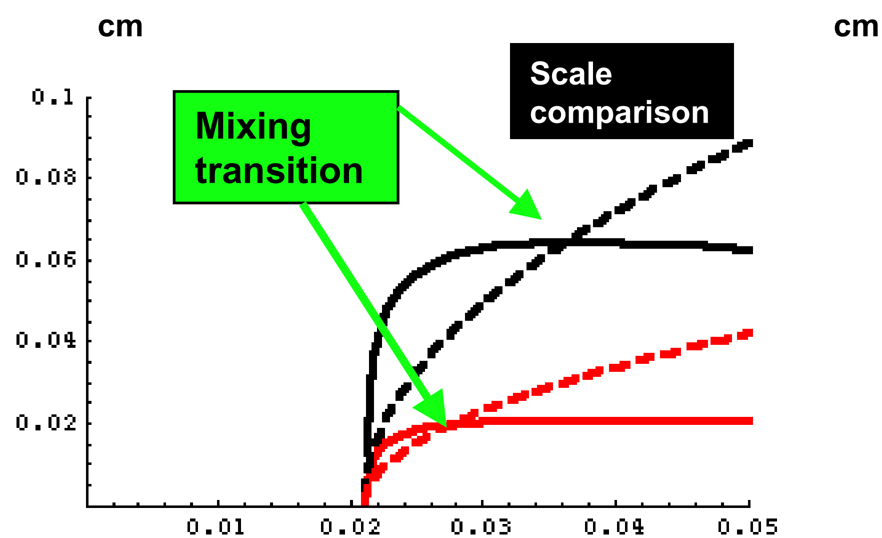
AWE Rocket-Rig Rayleigh-Taylor experiments by Read and Youngs can achieve the mixing transition







NaI Solution: black;
Pentane: red

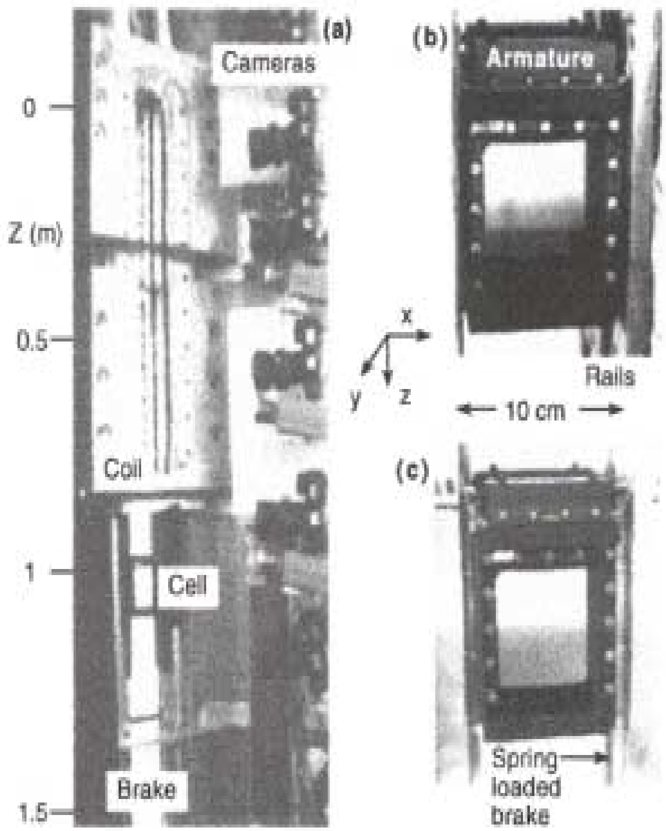


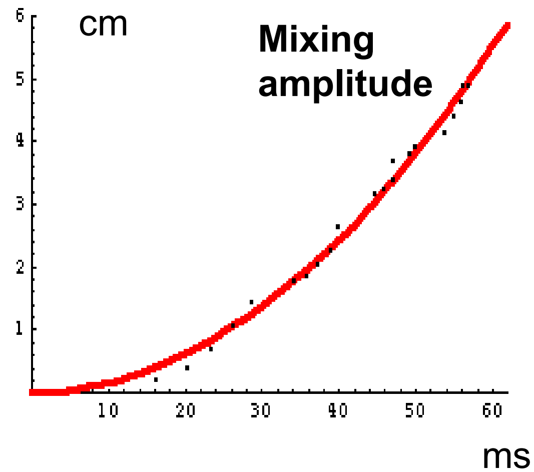
NaI Solution and Pentane:

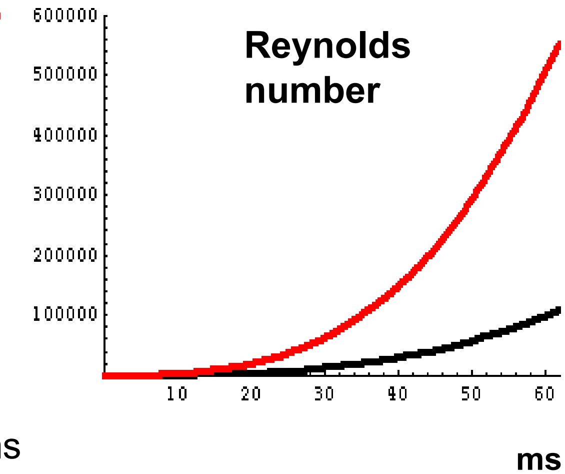
a = 27 g; A = 0.5 (Experiment # 33)

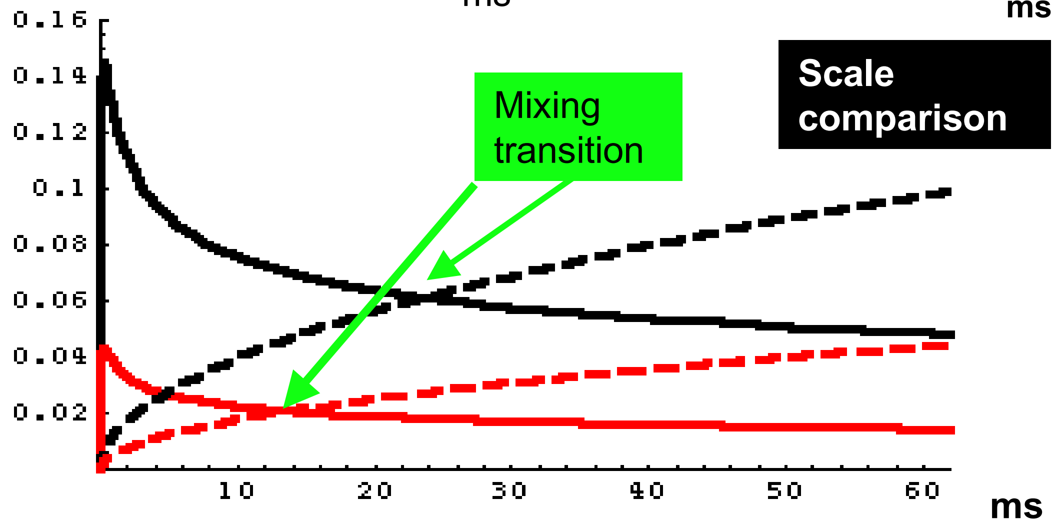
YZ_IWPCTM_113001–17

Linear Electric Motor Rayleigh-Taylor experiment can achieve the mixing transition after 1/3 of the duration







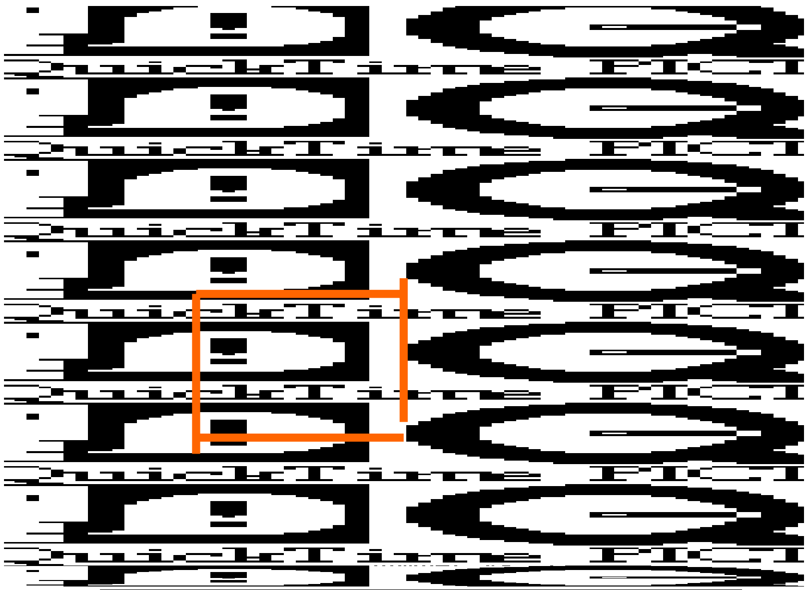


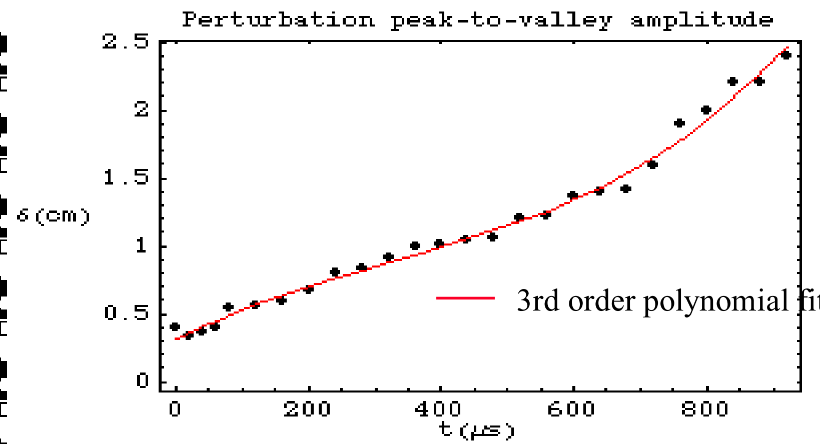
Constant acceleration with Water and Freon, A=0.22

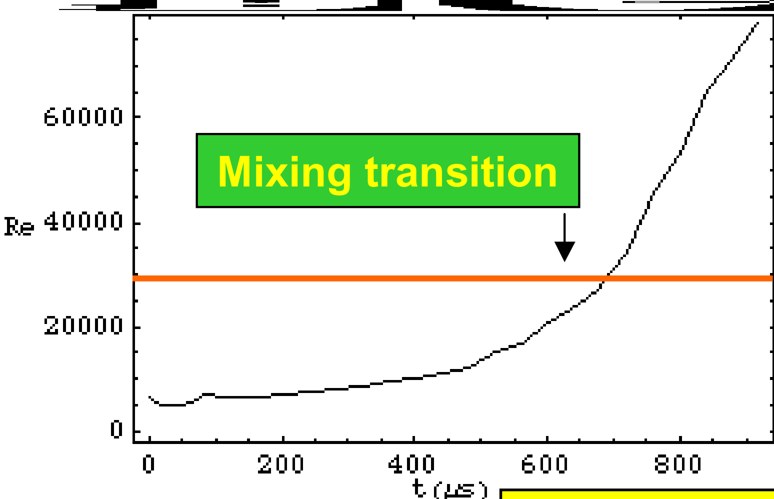
Water: black; Freon: red

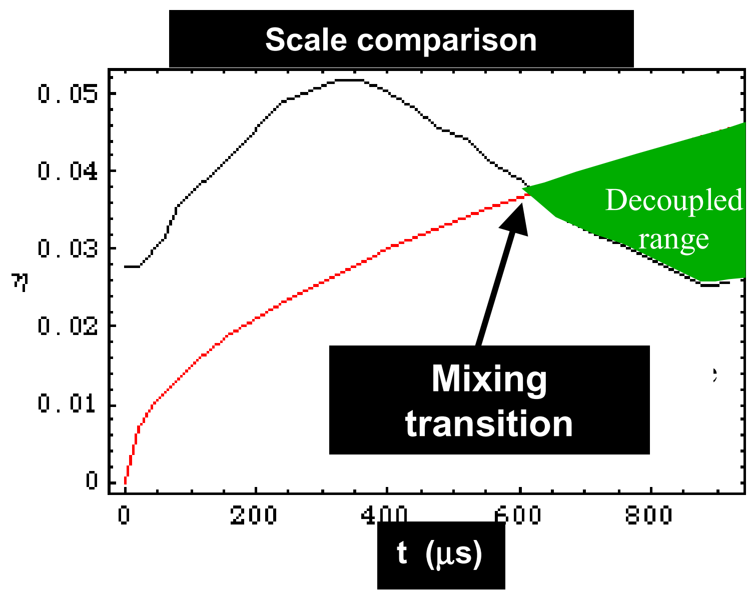
YZ_IWPCTM_113001–18

The turbulent transition time in the LANL gas curtain experiment can be determined by this new procedure



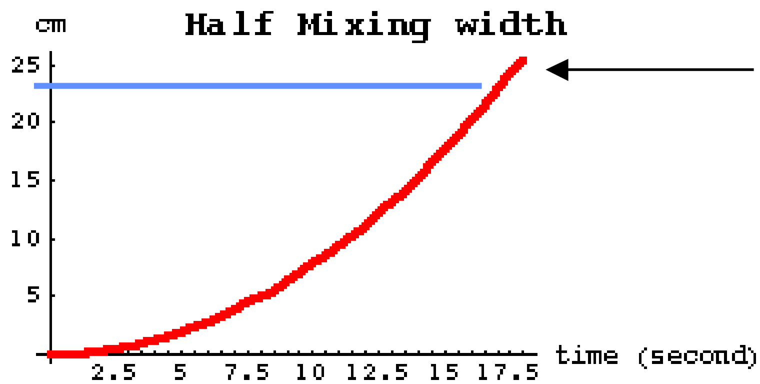




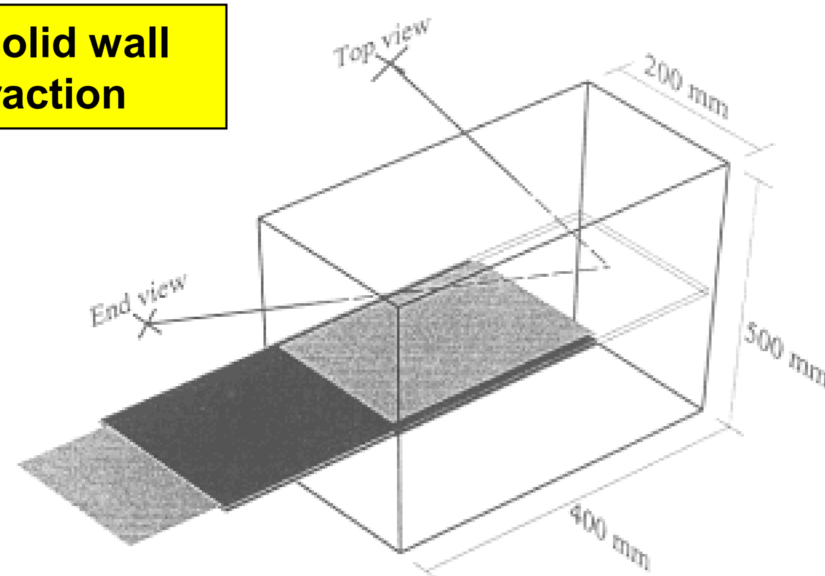


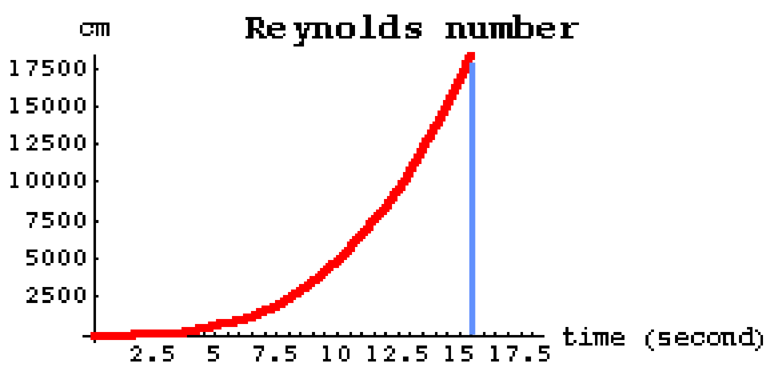
Rightly, Vorobieff, Martin, & Benjamin, Phys. Fluids 11(1), 186 (1999)

Rayleigh-Taylor experiments at Cambridge University can achieve Reynolds number ~ 1.75×10^5 in theory



Flow-solid wall interaction

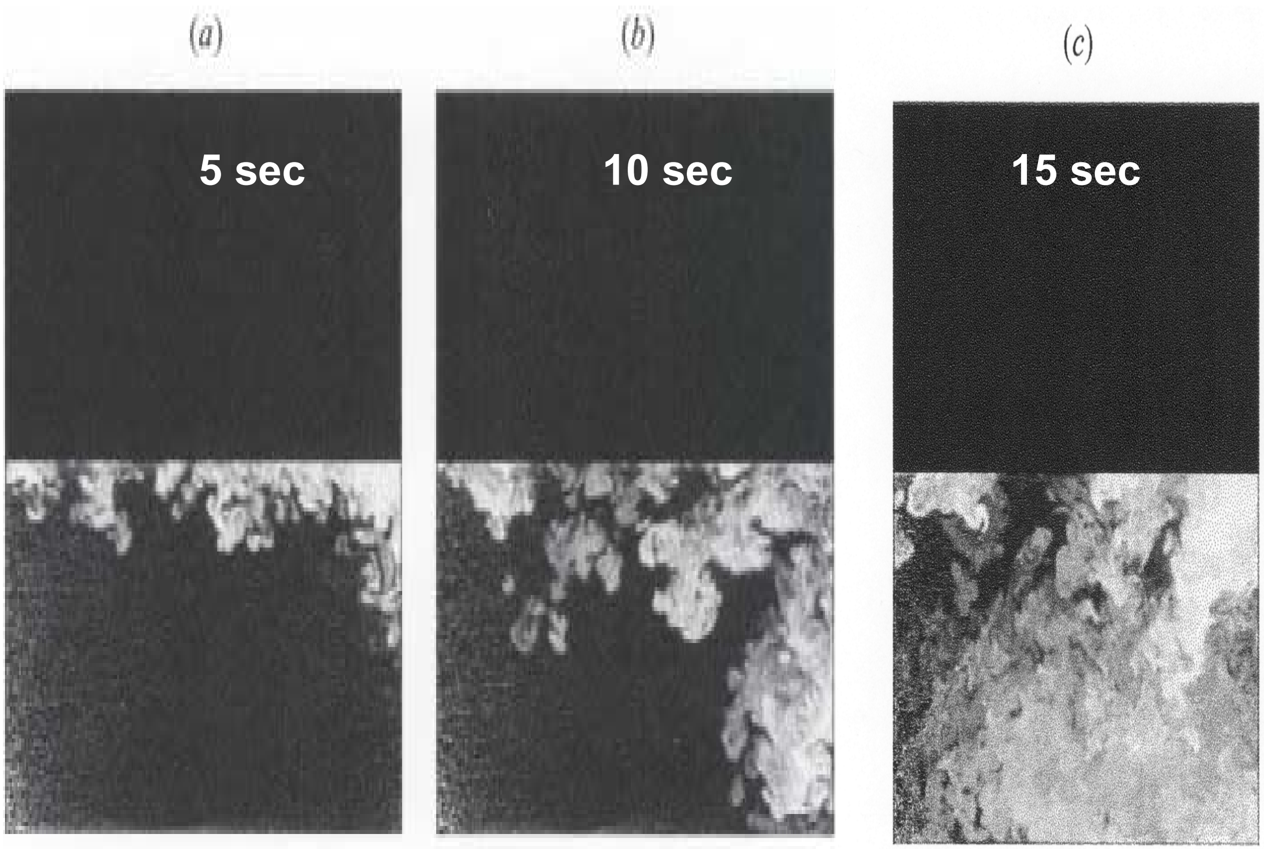


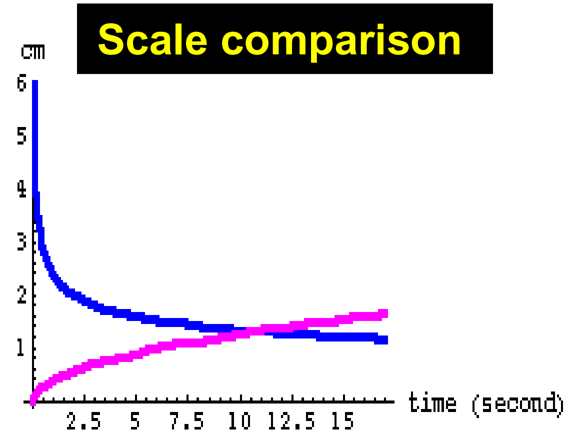


- **Unit gravitational acceleration a=1 g**
- **Miscible fluids were used**
- **Stainless steel barrier withdrawn manually**
- **200 mm × 400 mm × 500 mm (height)**

Atwood number ~ 0.002

RT induced flow field is contaminated around 10 seconds by the wake resulted from the barrier withdraw

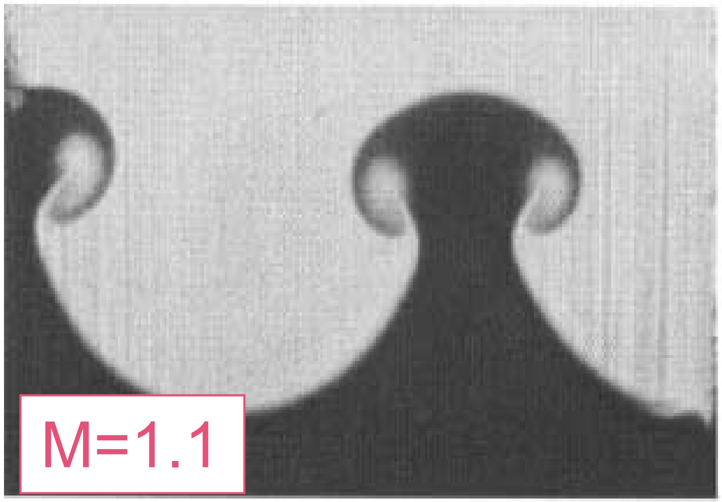


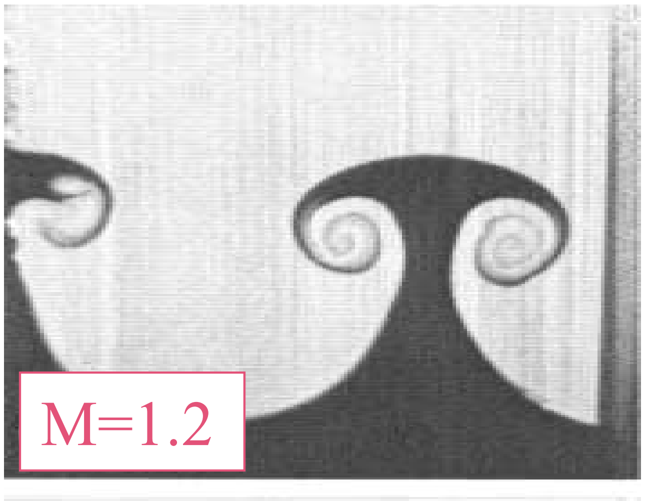


A challenge is to remove the wake so a RT induced mixing transition can be observed

Increasing the size of the tank will help, but cannot remove the contamination completely

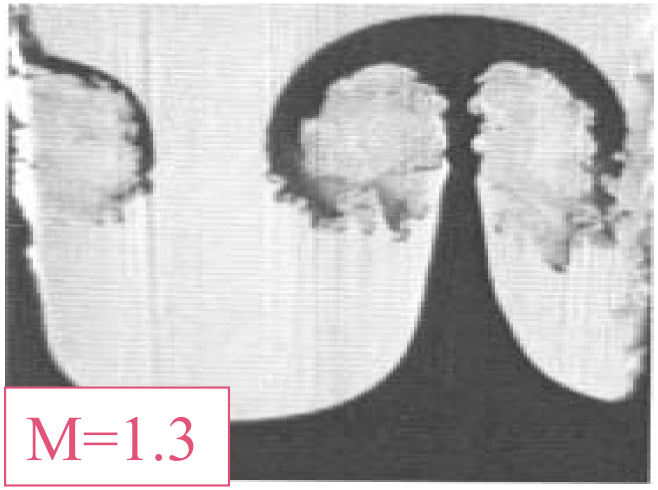
The time required for achieving mixing transition depends on the Mach number of the flow



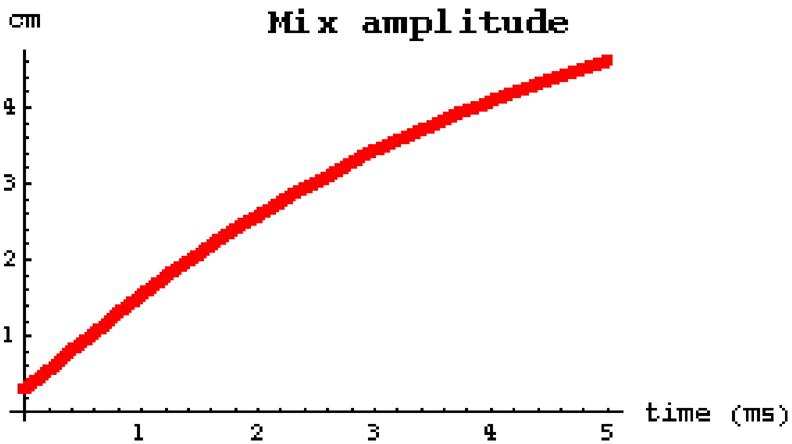


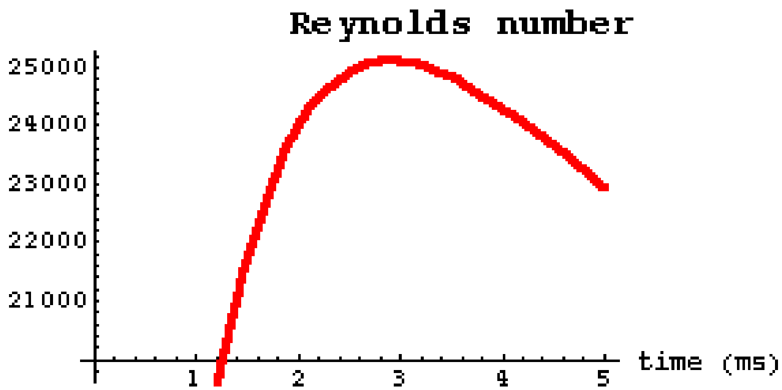
PLIF images assembled from incident shock waves with three different Mach numbers (~ 6 ms)

(J. Jacob, Univ. of Arizona)



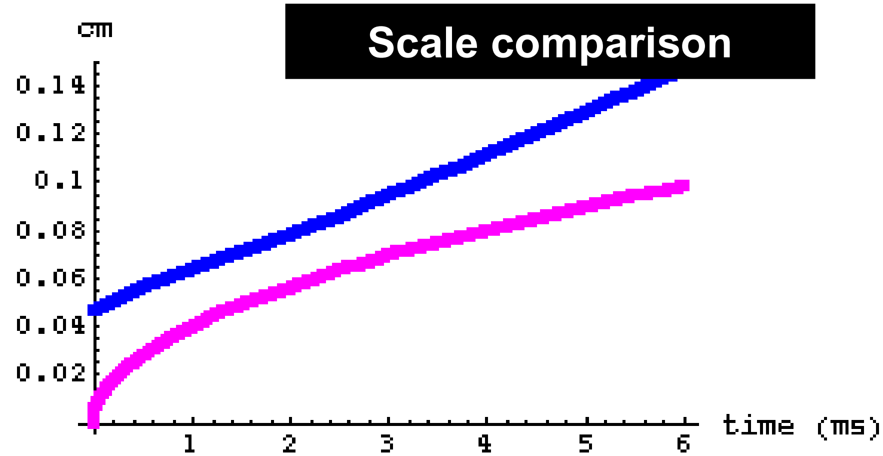
Jacob's experiment with Mach 1.2 incident shock wave does not achieve mixing transition





Minimum of Liepmann-Taylor and diffusion layer scales must exceed inner-viscous scale to achieve mixing transition

Scale comparison



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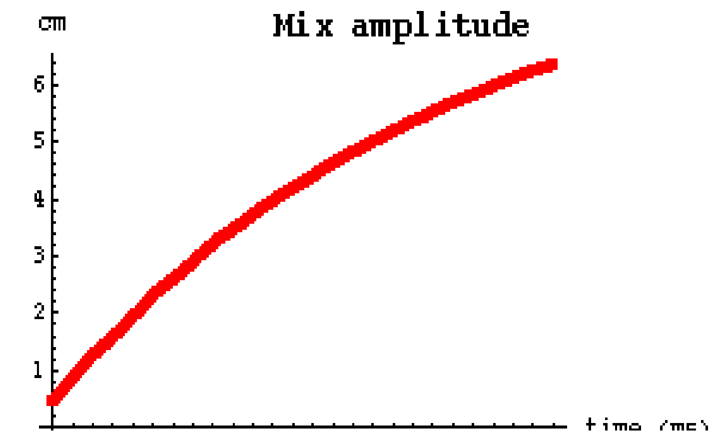
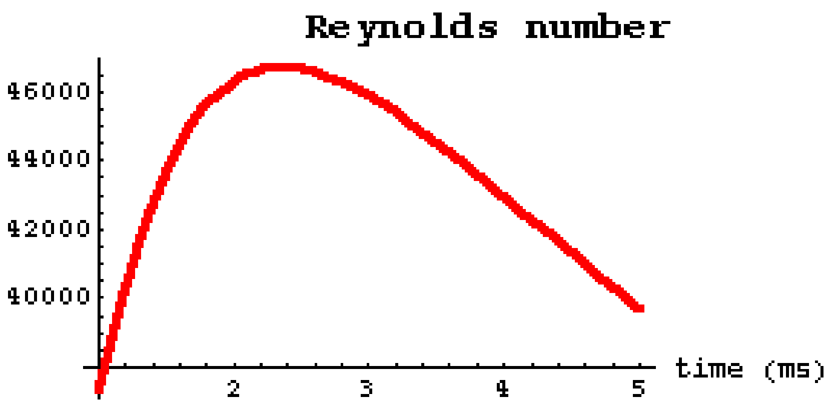
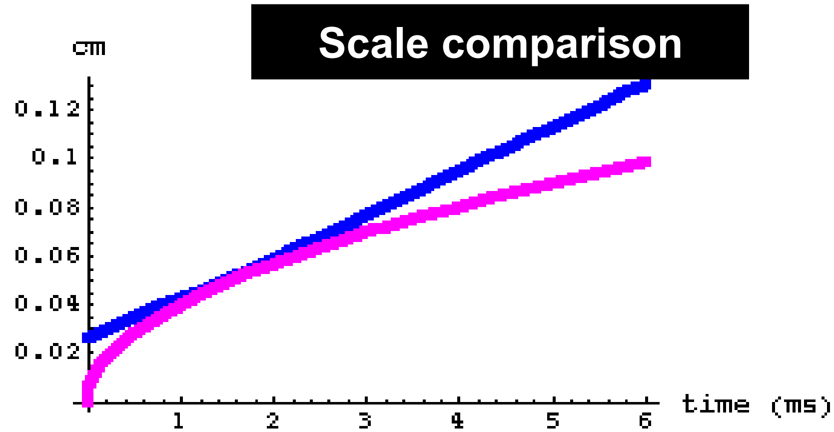
Mixing transition may occur when the Mach number of the incident shock is increased to 1.3

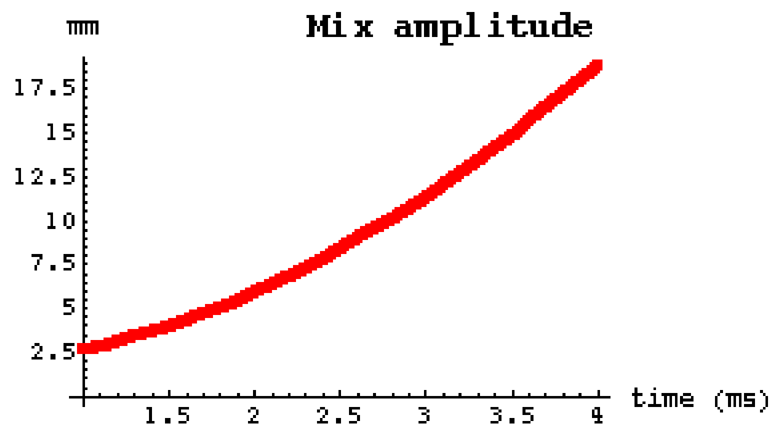


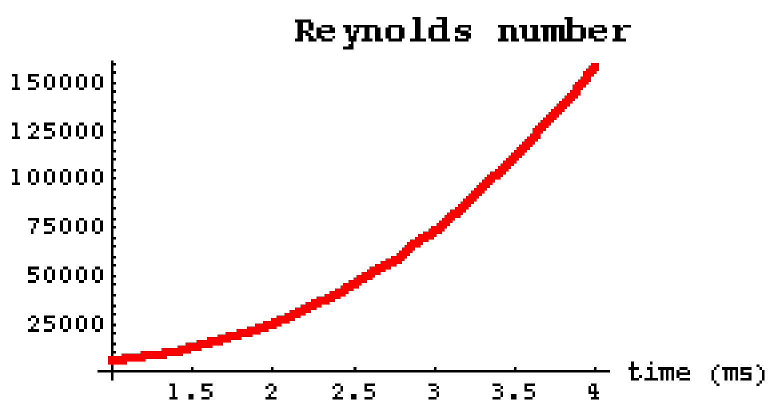
Mixing transition appears to occur at 2.5 ms



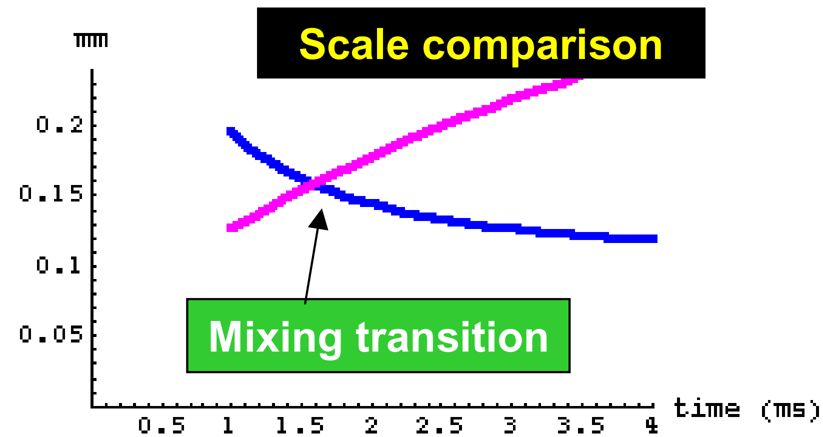


The prediction of mixing transition at 1.6 ms is consistent with the experiment



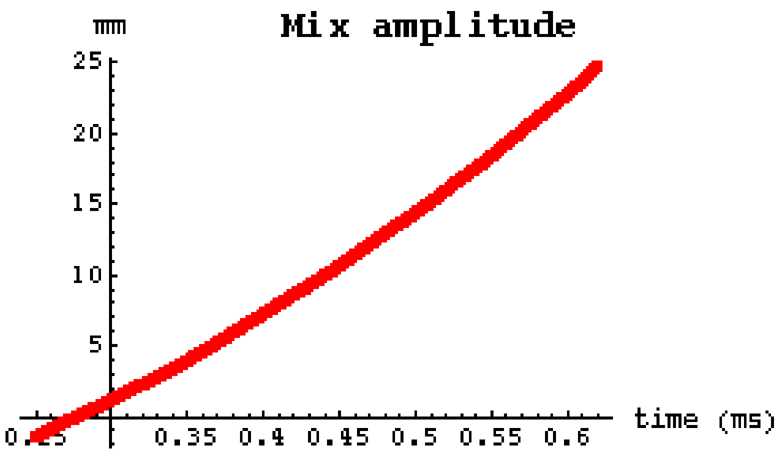


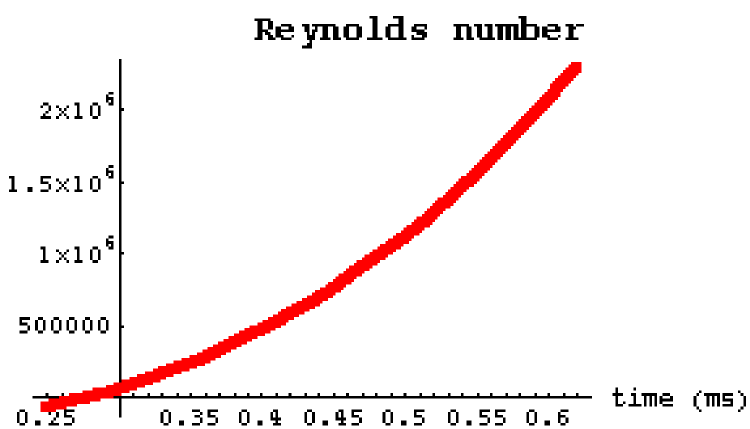
Experiment measurement indicates that transition occurs between 1.32 -- 2.15 ms



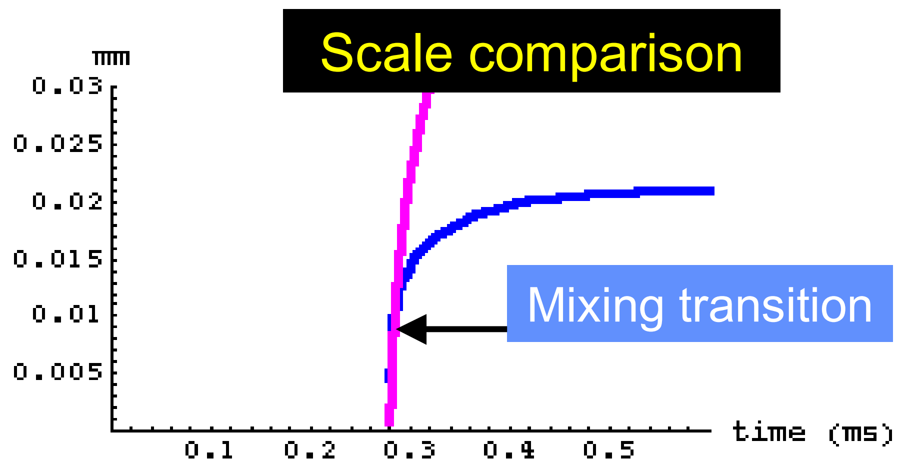
Meshkov Experiment #446

The prediction of mixing transition at 0.28 ms is consistent with the experimental measurement





Meshkov's results indicate that transition occurs between 0.20 -- 0.28 ms



Meshkov Experiment #422

A procedure to estimate the time required for mixing transition in time-dependent flows has been developed

Conclusions

- The flows induced by the RT and RM instabilities are time-dependent and have important applications in astrophysics and Inertial Confinement Fusion

- Both relevant spatial and temporal scales must be achieved

- Existing major experiments have been investigated regarding whether they have achieved turbulent state

- This procedure provides guidance for future designs of both classical fluid dynamics and laser-driven turbulent mixing experiments