STAML
Shock Tube & Advanced Mixing Laboratory

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Rayleigh-Taylor instability: An initial condition study

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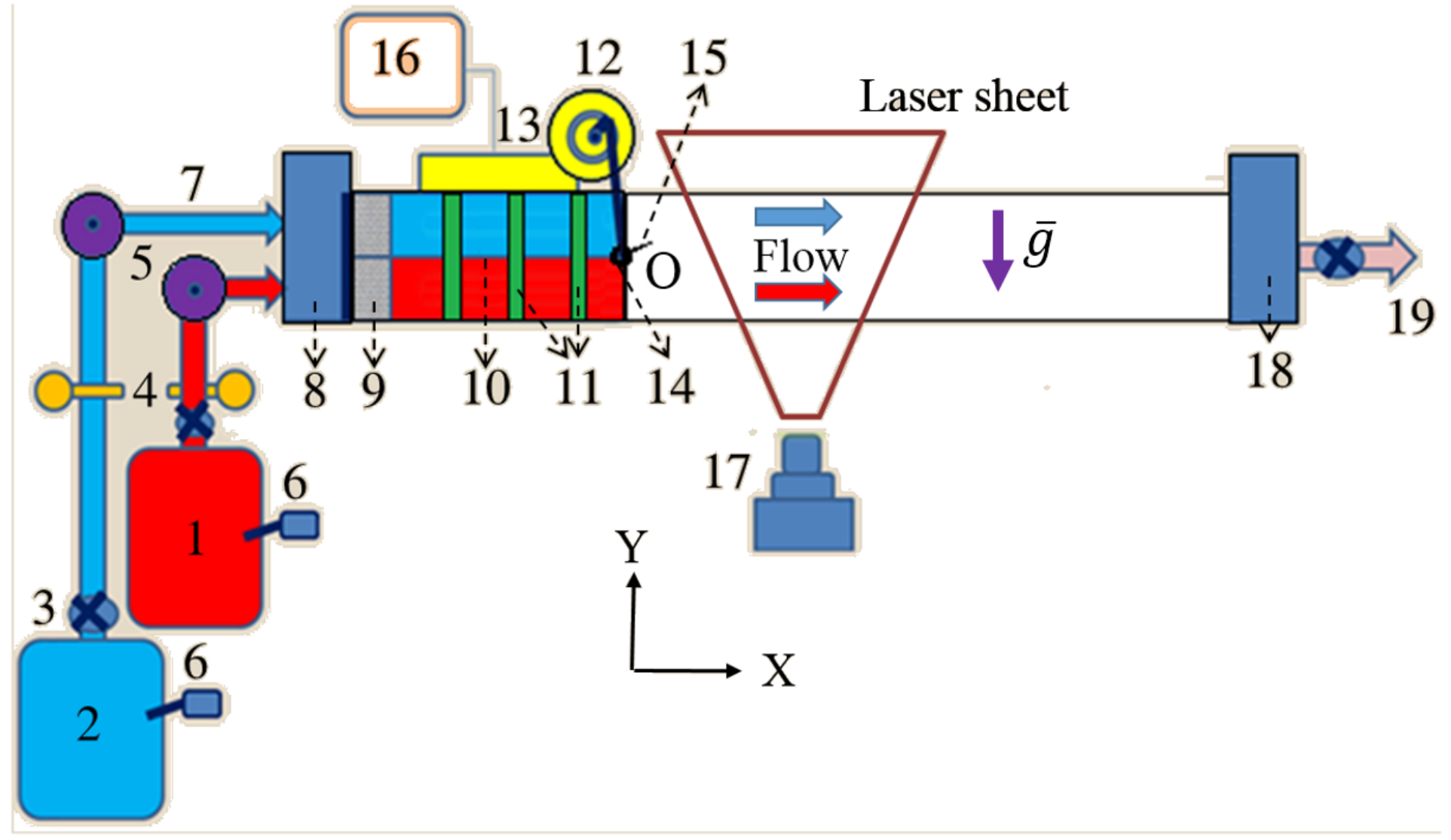
INTRODUCTION

- **Rayleigh-Taylor (RT)** instability occurs when density and pressure gradients are misaligned, $i.e. \nabla P . \nabla \rho < 0$. The baroclinic torque $-\nabla \times (\frac{\nabla P}{\rho})$ is the source of initial vorticity
- In the current study using the Water Channel facility, an initial unstable stratification of cold and hot water streams are acted upon by gravity
- A servo controlled flapper mechanism provides precise initial perturbations at interface of the cold and hot water streams
- Stages of RT evolution with time: Linear → Non-linear (mode coupling) → Turbulent

Motivation

- RTI is observed in many natural phenomena such as clouds, salt-water domes, astrophysical events ($e.g.$ nebulae)
- RTI is also witnessed in several applications such as in the ICF (Inertial Confinement Fusion) and spray ignition in engines etc.

EXPERIMENTAL SETUP



1. Hot water tank	8. Inlet plenum	15. Flapper
2. Cold water tank	9. Flow straighteners	16. Computer
3. Valve	10. Splitter plate	17. Camera
4. Flow meter	11. Wire mesh	18. Exit plenum
5. Pump	12. Servo motor	19. Water outlet
6. Thermostat	13. Servo controller	O: Origin
7. Piping	14. Connecting bars	

Figure 1: Schematic of the Water Channel setup

Flow parameters

- U = 4.5 cm/s
- $T_{hot} - T_{cold} \approx$ 5.0°C
- A_t = 1-2$\times 10^{-3}$

Diagnostics

- High resolution imaging
  - Line of Sight (LOS) imaging
- Thermocouple measurement
  - 1kHz temporal resolution
  - Density field extracted
- Planar Laser Imaging of Fluorescence (PLIF)
  - 15Hz temporal resolution
  - 2.0MP spatial resolution
  - Concentration (passive scalar) field extracted
- Particle Image Velocimetry (PIV)
  - 30Hz temporal resolution
  - 1.4MP spatial resolution

PLIF EXPERIMENTAL PARAMETERS

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Initial conditions

- Initial condition

$$\frac{a_i}{\lambda_i} = 0.1$$
$$y = \Sigma a_i sin(\omega_i t + \beta_{i-1})$$
$$\omega_i = \frac{2\pi U}{\lambda_i}$$

Broadband case

- A waveform similar to Olson & Jacobs (2009) RT experiment was used
- The wavelengths were rescaled to $\lambda \epsilon$ [2.04-4.0]cm, so that they are comparable to case 1

Imaging details

- Rhodamine 6G as fluorescein
- $Sc \approx$1500, $Pr \approx$ 7.0
- $x \ \epsilon [8.9 - 67.5]$, $y \ \epsilon [0 - 38.5]$, $z \approx 0$cm (for all images in fig. 2)
- Times t_1^* and t_2^* correspond to x_1 and x_2 respectively (fig. 4(a))

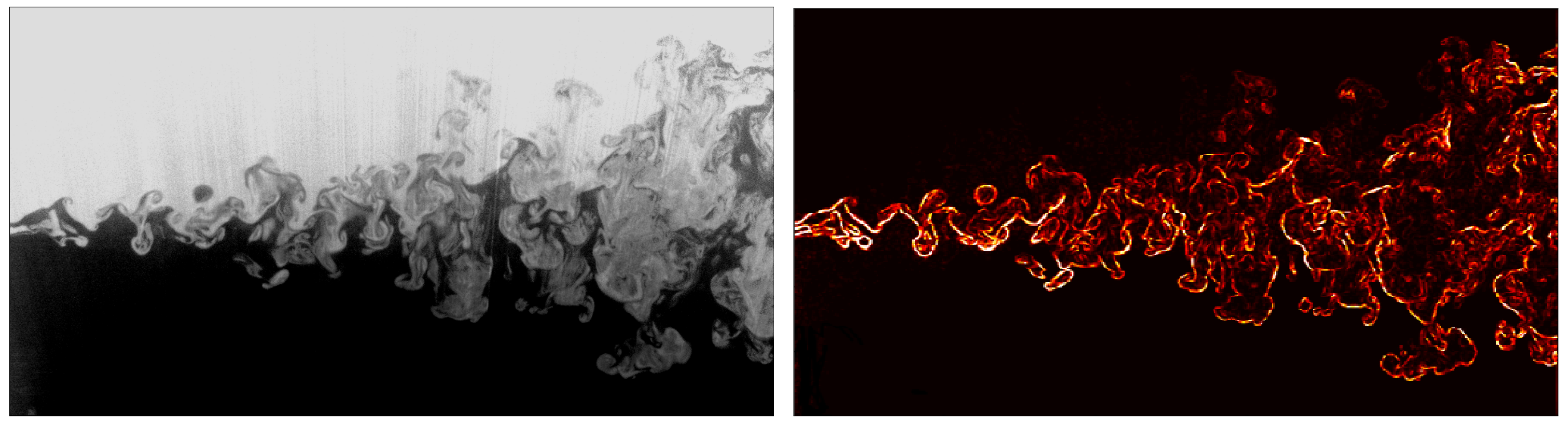
Table 1: List of experiments

IC mode type	Remarks	Case #	Wavelength			Phase angle		A_t
			λ_1 (cm)	λ_2 (cm)	λ_3 (cm)	$\beta_1(^\circ)$	$\beta_2(^\circ)$	$(\times 10^{-3})$
Single	Increasing λ	1	0	-	-	-	-	1.00
		2	2	-	-	-	-	1.00
		3	4	-	-	-	-	1.03
		4	6	-	-	-	-	1.02
		5	8	-	-	-	-	1.06
Binary	Increasing β	6	8	2	-	0	-	1.07
		7	8	2	-	30	-	1.11
		8	8	2	-	45	-	1.11
		9	8	2	-	60	-	1.13
		10	8	2	-	90	-	1.12
		11	8	2	-	120	-	1.88
	Increasing λ_2	12	8	4	-	45	-	1.00
		13	8	6	-	45	-	1.06
Multi	Inc. # of modes	14	8	4	2	45	90	1.07
		14	8	4	2	45	90	1.10
		15	8	6	4	45	-	1.06
		16	8	6	5	45	-	1.11
		17	8	7	6	45	-	1.13
		18	Broadband IC					2.00

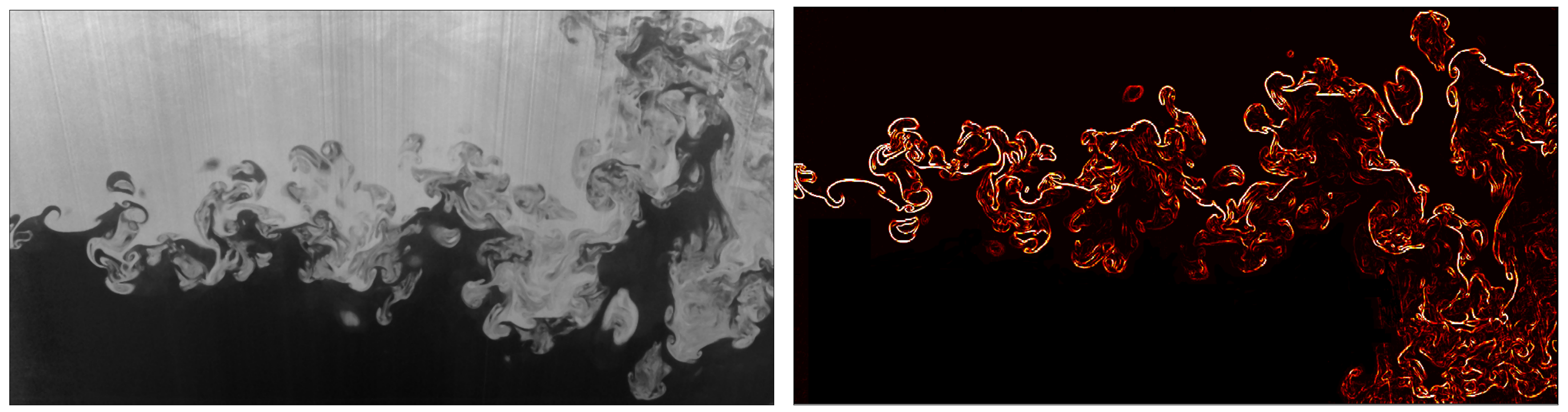
Analysis details

- Background intensity and laser plane divergence corrected. Linear attenuation of light with y at low dye concentration
- Ensemble average of 800 images used to calculate mixing width. Equivalent wavelength, λ_{eq} based on initial height

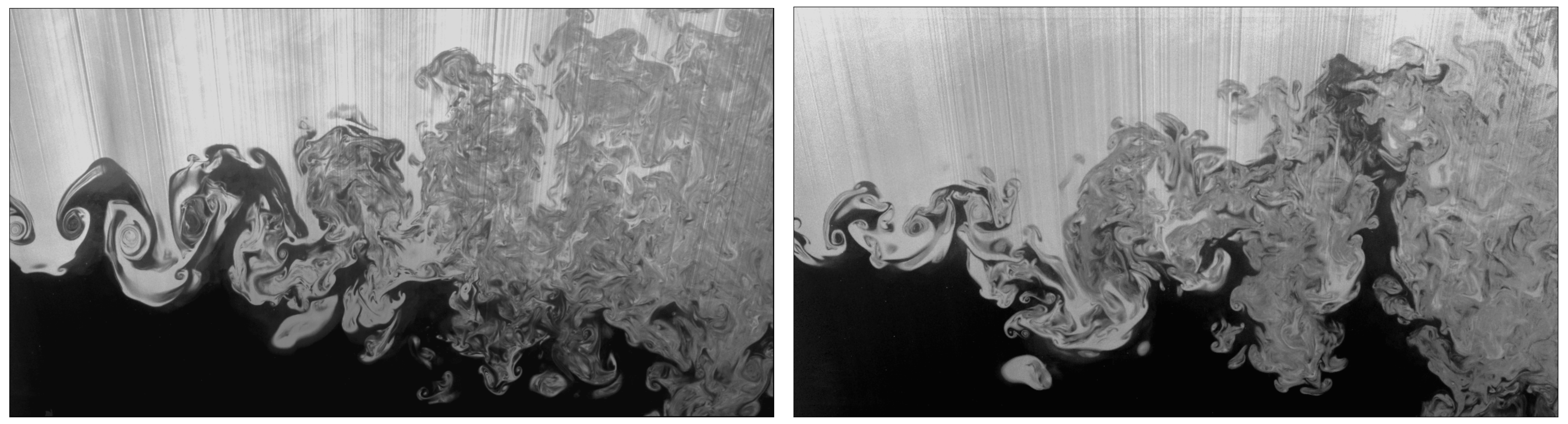
FLOW VISUALIZATION



(a) Without flapper motion (case 1) (b) Qualitative scalar dissipation rate contours (case 1)



(c) Broadband with 11 modes (case 18) (d) Qualitative scalar dissipation rate contours (case 18)

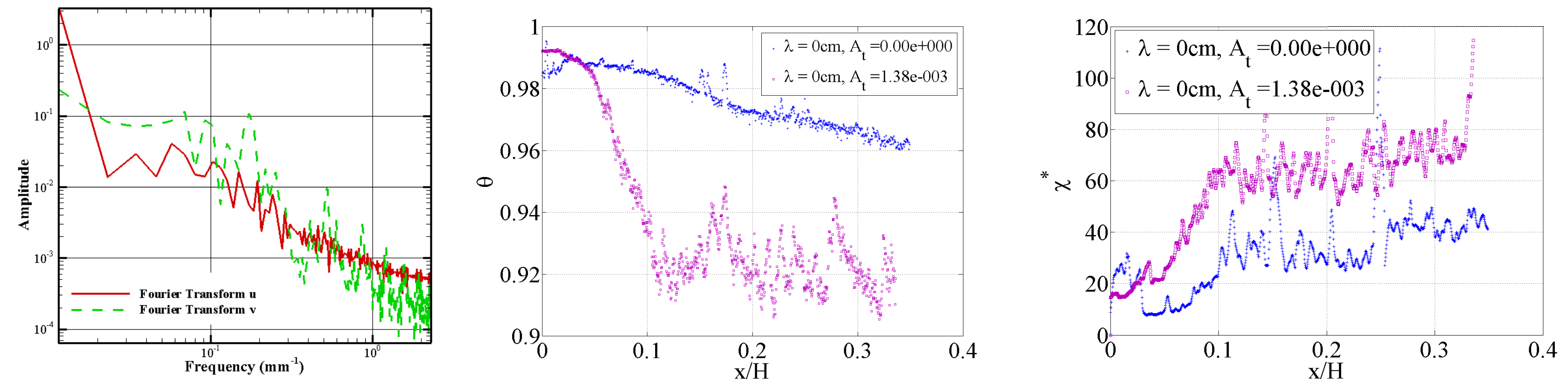


(e) $\lambda = 8cm$ (case 5) (f) 7 modes (case 17)

Figure 2: Flow visualization for select cases

EFFECT OF WAKE ON A CONVECTIVE RT SETUP

- The wake interacts with RT evolution. PIV measurement indicates that the wake is highly symmetric about the splitter plate
- The peak wavenumbers in v spectrum (fig. 3(a)) correspond largely to the splitter plate thickness and spacing between the wire meshes
- The molecular mixing parameter, θ, obtained from PLIF images indicate that the effect of the wake in diffusion mixing is very small compared to that of baroclinic vorticity
- χ^* plotted along $y \approx 0$ (fig. 3(c)). Here $t = \frac{x}{U}$ using Taylor's hypothesis



(a) Normalized power spectra of u and v for wake flow only (b) Molecular mixing parameter with & without RTI (c) Scalar dissipation rate with & without RTI

Figure 3: Wake effect on RT mixing

ACKNOWLEDGEMENT

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NOMENCLATURE & DEFINITIONS

P	Pressure
ρ	Density
g	Acceleration due to gravity
U	Mean convective velocity
T	Temperature
h	Total mixing width, $h = h_{(f_c=0.95)} - h_{(f_c=0.05)}$
f	Mole fraction of fluid
θ	Molecular mixing parameter, $\theta = 1 - \frac{B_0}{B_2}$, $B_0 = \lim_{T\to\infty} \frac{1}{T}\left[\rho'^2 dt/(\rho_c - \rho_h)^2\right]$, $B_2 = f_c f_h$
B_0	Density fluctuation self-correlation for miscible fluids
B_2	Density fluctuation self-correlation for distinct fluids
t	Time, $t^* = \frac{t}{\tau}$, with time scale, $\tau = \sqrt{\frac{\lambda_{eq}}{A_t g}}$
T	Total time of observation
χ	Instantaneous scalar dissipation, $\chi^* = \int_{-H/2}^{H/2} \frac{\lvert\nabla<f_c(x,y)>\rvert^2>}{Sc}\frac{dy}{H}$
Sc	Schmidt number

H	Total channel height
λ	Wavelength of initial condition
y	Displacement of initial condition
a	Amplitude of initial condition
ω	Angular frequency
β	Phase angle of initial condition
Pr	Prandtl number
u	Streamwise velocity
v	Spanwise velocity
(x, y, z)	Coordinates (refer fig. 1)

Subscripts

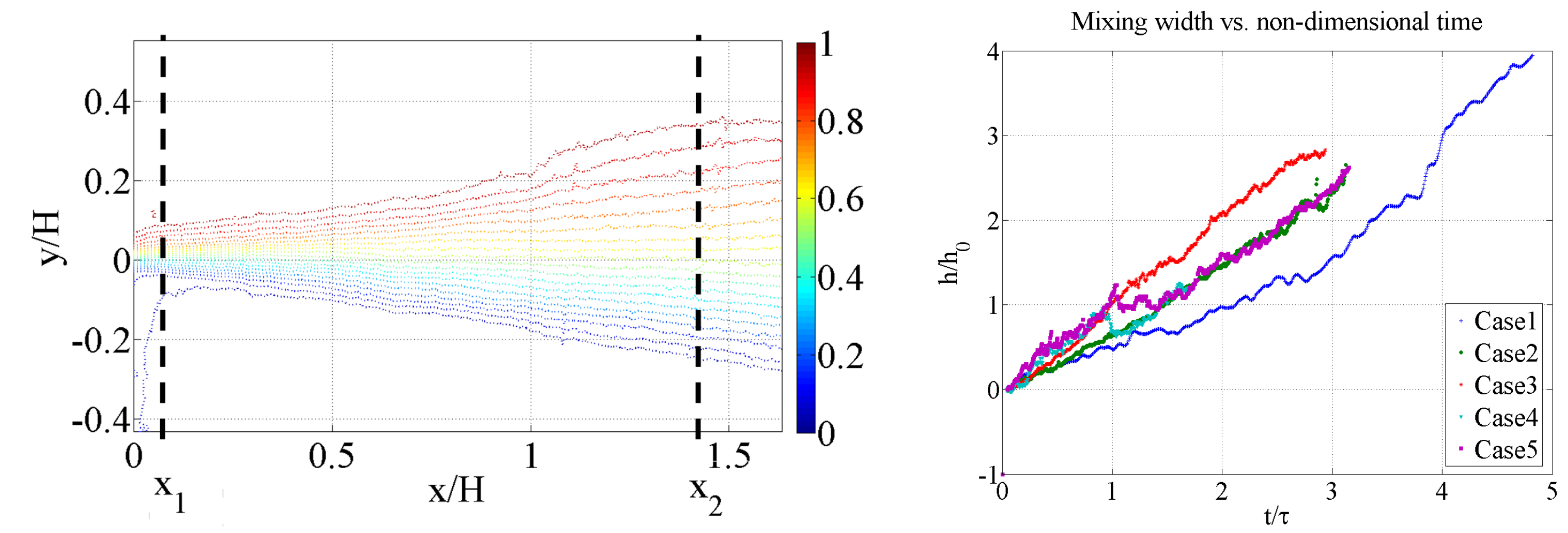
$'$	Fluctuation
$*$	Non-dimensionalized

Subscripts

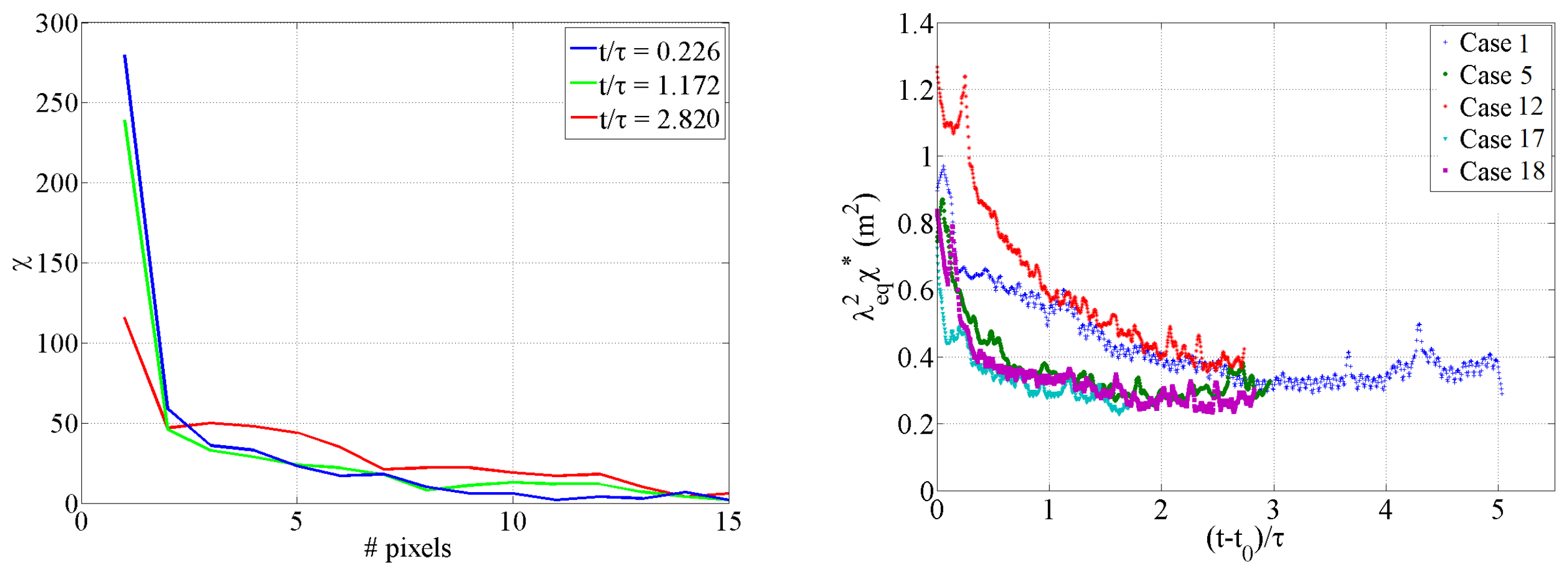
c	Cold
h	Hot
eq	Equivalent
<>	Time mean

RESULTS & DISCUSSION

RT Mixing study



(a) Contours of f_c for case 1 (b) Variation of mixing width



(c) Histogram of scalar dissipation rate for case 18 (d) Variation of scalar dissipation rate

Figure 4: Variation of integral mixing parameters

CONCLUSION & FUTURE WORK

- In the mode coupling regime, the growth rates are comparable with each other for different cases (fig. 4(b)). However, saturation has not been attained for many cases
- The fastest growth rate is of the broadband case while the slowest corresponds to the no flapper motion case.
- Scalar dissipation rate scales as λ_{eq}^{-2} and flattens out at late-times, showing independence of fine-scale mixing (fig. 4(d))
- Simultaneous PLIF + PIV data of these cases will help study of flow characteristics such as anisotropy and saturation, and validation of computational RT codes