A scale-by-scale analysis of transfer in a turbulent separated flow

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Massive separations

Boundary and initial conditions

Shedding

Flapping

Universality?

✓

Scaling laws

✓

Robustness of control

Numerical predictions?

What dependencies?

ENTRAINMENT: a big picture?

Chapman et al. (1958): backflow - shear layer entrainment
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Universality?

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Chapman et al. (1958): backflow - shear layer entrainment
Entrainment & Interfaces

RRI: Recirculation Region Interface
TNTI: Turbulent/Non-Turbulent Interface

\[ u = U + u' \]
Entrainment & Interfaces

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RRI: Recirculation Region Interface
TNTI: Turbulent/Non-Turbulent Interface

\[ u = U + u' \]
TNTI

✓ Physical border: 

  *entrainment external flow* $\longleftrightarrow$ *separated flow.*

✓ Highlights multiscale entrainment mechanisms

  ▶ Small scales: viscous nibbling  
  Corrsin et Kistler (1955)
  ▶ Large scales: entrainment/organisation of flow  
  Chauhan et al. (2014), Mistry et al. (2016)

✓ A global tracer (beware of inhomogeneity and anisotropy...)

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Interface generalities
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✓ A global tracer (beware of inhomogenity and anisotropy...)

RRI

✓ Not much attention to interface per se.

✓ An iso-level turbulent interface (Pope 1988).
  ▶ Multiscale nature.
  ▶ A role in entrainment.

✓ Strong sensitivity to control systems expected.
Interfaces and separation control

✓ **Contribute to understanding of massive separations**
  ▶ Connections between different part of flow.
  ▶ Interface as tracer of upstream (TBL) history?

✓ **Universal entrainment behaviors (e.g. scaling laws)?**

✓ **Transfer mechanisms as control mechanisms?**
✓ Integral view:
  Measure intensity of mean entrainment through RRI and TNTI.
  ▶ Quantitatively relevant?

✓ Local view:
  Streamwise evolution of mean fluxes.
  ▶ Any connection between RRI, TNTI and flow topology?
  ▶ Mean scaling law?

✓ Scale-by-scale analysis
  ▶ Identify entrainment mechanisms
  ▶ A scaling law for all turbulent scales?
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→ Mass entrainment (for now...).
Experimental set up

Descending ramp 25 deg

\[ Re_h = \frac{U_{ref} h}{\nu} \approx 30000 \text{ to } 70000. \]
\[ Re_\theta = \frac{U_{ref} \theta}{\nu} \approx 2000 \text{ to } 5500 \text{ (at reference section).} \]
\[ A/R \approx 17: \text{ 2D mean flow.} \]
Main PIV set up

✓ Nd:Yag laser (532 nm, 2 x 200 mJ).
✓ 2 frames 4032 x 2688 px, Zeiss 50 mm ZF Makro Planar T*.
✓ Total field of view 9 x 2.5 h
✓ LaVision GPU direct correlation, multipass, final correlation window 16 x 16 px.
✓ Final PIV resolution 0.04h.
Interface detection

\[ \tilde{k} = \frac{1}{9} \sum_{m, n} \left[ (u_{m,n} - U_\infty)^2 + (v_{m,n} - V_\infty)^2 \right] \]

Chauchan et al. (2014a).

- \( \tilde{k} = \tilde{k}_{\text{thr}} \)
- \( \tilde{k}_{\text{local}} \) average
- Filtered
- PIV correlation
- Pockets and islands
Interface detection

\[ \tilde{k} = \sum_{m, n = -1}^{1} \left[ (u_m, n - U_\infty)^2 + (v_m, n - V_\infty)^2 \right] \]

TNTI

Chauchan et al. (2014a).

\[ \tilde{k} = \tilde{k}_{\text{thr}} \]

\[ RRI \]

\[ u = 0 \]

Filtered

\[ \check{\text{PIV}} \]

Correlation

\[ \check{\text{Pockets and islands}}. \]

\[ \check{\tilde{k}_{\text{local average}}} \].

RRI \quad u = 0
Interface detection

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**RRI**  \( u = 0 \)
Interface detection

Filtered

- PIV correlation.
- Pockets and islands.
- $\tilde{k}$ local average.

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RRI $u = 0$
Integral view: mean mass balance

Is entrainment through the TNTI and the RRI relevant?

\[
\dot{m}_i = -\rho \int_{L_i} \vec{n}(s) \cdot \vec{U}(s) \, ds
\]

\[
\dot{m}_i > 0 \text{ if incoming}
\]

\[
\sum_i \dot{m}_i = 0
\]

\[
\frac{\dot{m}_3}{\dot{m}_1} = 1.27, 1.18, 1.28, 1.26, 1.31
\]

\[
\frac{\dot{m}_4}{\dot{m}_1} = 0.38, 0.38, 0.39, 0.38, 0.39
\]

\[
\frac{\left( \sum_i \dot{m}_i \right)}{\dot{m}_1} = 0.11, 0.20, 0.10, 0.12, 0.08
\]
Integral view: mean mass balance

Is entrainment through the TNTI and the RRI relevant?

\[ \dot{m}_2 = -\rho \int \mathbf{n}(s) \mathbf{U}(s) \, ds \]

\[ \dot{m}_3 > 0 \text{ if incoming} \]

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2D flow, stationary mean recirculation region! $\rightarrow \dot{m}_2 = 0$
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Finer insight from the streamwise evolution of local mass fluxes...
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Finer insight from the streamwise evolution of local mass fluxes...

\[ \dot{m}_i = -\rho \int_{L_i} \bar{n}(s) \bar{U}(s) \, ds \]

\[ \dot{m}_{x2} = \frac{d\dot{m}_2}{ds} \approx -\rho V(s) \]

\[ \dot{m}_{x4} = \frac{d\dot{m}_4}{ds} \approx -\rho (U(s) \theta(s) + V(s)) \]

\[ \cos(\theta) \sim 0.98 \text{ along RRI} \]
\[ \theta \sim 0.03 \text{rad} \text{ along TNTI} \]
Local view: local mean fluxes

\[ \dot{m}_{c2}/(\rho U_1) \]

RRI fluxes

\[ \dot{m}_{c4}/(\rho U_1) \]

TNTI fluxes

- \( Re_\theta = 2006; \)
- \( Re_\theta = 3262; \)
- \( Re_\theta = 4122; + \)
- \( Re_\theta = 4738; \)
- \( Re_\theta = 5512 \)

Scaling:

\[ U_1 = -\dot{m}_1/\left(\rho \int_{L_1} ds\right). \]

Good correlation with

\[ C_{px} = h/\left(0.5 \rho U_2 \infty \right) \frac{dp}{dx} \text{ (from PIV).} \]
Local view: local mean fluxes

RRI fluxes

TNTI fluxes

✓ Scaling:

$L_R - U_1$ on both interfaces.

$U_1 = -\dot{m}_1 / (\rho \int_{L_1} ds)$.

○ $Re_\theta = 2006$; ◇ $Re_\theta = 3262$; □ $Re_\theta = 4122$; + $Re_\theta = 4738$; △ $Re_\theta = 5512$
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- $Re_\theta = 2006$; $Re_\theta = 3262$; $Re_\theta = 4122$; $Re_\theta = 4738$; $Re_\theta = 5512$
Local view: further considerations

✓ Mean mass flux scaling

Mean mass fluxes scale with TBL properties at x/h = -9!

Correlation:

\[ \dot{m}_{x_i} - C_{p_x} \]

\[ L_R = L_R(Re_\theta, h) \]

\[ U_1 \sim U_\infty (1 - \theta H_12 / \delta) \]

Open question: what link between pressure gradient and TBL properties?
Mean mass flux scaling

\[ U_1 \sim U_\infty \left( 1 - \frac{\theta H_{12}}{\delta} \right) \]
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✓ \( \dot{m}_{xi} - C_{px} \) correlation

\( C_{px} \): a connection between local RRI and TNTI fluxes, on scales \( \sim L_R \).
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Scale-by-scale analysis

Assign a **mass entrainment contribution** to each scale that **wrinkles** the interfaces.
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✓ What turbulent scales contribute the most to mass entrainment?
✓ Is scaling of mean mass entrainment still valid at all scales?
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**Instantaneous local mass fluxes.**

\[
\frac{dm(s)}{ds} = \rho \vec{n}(s) \vec{v}_E(s) \, ds
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\[
\dot{m}(s) = \rho \tilde{n}(s) \vec{v}_E(s) \, ds = \rho \tilde{n}(s) (\vec{v}(s) - \vec{v}_{interf}(s)) \, ds
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**Instantaneous local mass fluxes.**

\[ d\dot{m}(s) = \rho \bar{n}(s) \vec{v}_E(s) \, ds = \rho \bar{n}(s) (\vec{v}(s) - \vec{v}_{interf}(s)) \, ds \]

**Fourier spectra of** \( d\dot{m}(s) \)  
\[ d\dot{m}(s) \rightarrow \Psi_{d\dot{m}}(k_s) \quad k_s \text{ wavenumber} \]

Chauhan et al. (2014a).
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\]

**Fourier spectra** of \(\mathrm{d}m(s)\)

\[
\mathrm{d}m(s) \rightarrow \Psi_{\mathrm{d}m}(k_s) \quad k_s \text{ wavenumber} \quad r = \pi/k_s \text{ a turbulent scale}
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**Fourier spectra of** \( \dot{m}(s) \)

\[
\dot{m}(s) \rightarrow \Psi_{\dot{m}}(k_s) \quad k_s \text{ wavenumber} \quad r = \pi/k_s \text{ a turbulent scale}
\]

\[
\bar{v}_{\text{interf}}(s) \rightarrow \text{Interface displacements} \rightarrow \text{TR-PIV} \rightarrow \text{UNAVAILABLE}
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**Fourier spectra** of \( \dot{m}(s) \)  
\( \dot{m}(s) \rightarrow \Psi_{\dot{m}}(k_s) \) \( k_s \) wavenumber \( r = \pi/k_s \) a turbulent scale

\( \vec{v}_{\text{interf}}(s) \rightarrow \) Interface displacements \( \rightarrow \) TR-PIV \( \rightarrow \) UNAVAILABLE

However, for **TNTI only**:

\[
\vec{v}_E(l) = \vec{v}(l) - \vec{v}_{\text{TNTI}}(l) \approx -2\nu_j S_{ij} / \tilde{K}_{th}
\]

S.b.s. analysis: enhanced PIV data

✓ 1 frame 4032 x 2688 px, Nikon 200 mm Nikkor ED AF Micro.
✓ Field of view 1.5 x 1.2 h
✓ 16 x 16 px
✓ Final PIV resolution $0.0065 \, h \approx 4-6 \, \eta_k$. 
Scaling: $\theta - U_1$

- Large scale units for whole spectrum.
- $\Psi_{\text{d}m}^\theta = \Psi_{\text{d}m} / (U_1)^2$
- $k_s^\theta = k_s \theta$

$Re_\theta = 2006; \diamond Re_\theta = 3262; \Box Re_\theta = 4122; + Re_\theta = 4738$
Scaling: $\theta - U_1$

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- $\Psi_{\theta d\dot{m}} = \Psi_{d\dot{m}} / (U_1)^2$
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Re$\theta$ effect on peak.

$\circ Re_\theta = 2006$; $\diamond Re_\theta = 3262$; $\square Re_\theta = 4122$; $+$ $Re_\theta = 4738$
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 Mass entrainment at small scale.
  - *Nibbling* at TNTI.

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Entrainment: a multiscale phenomenon!

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- $Re_\theta = 3262$;
- $Re_\theta = 4122$;
- $Re_\theta = 4738$
Mean mass fluxes scale with global properties of TBL upstream of separation ($x/h = -9$)

At least for TNTI, a TBL-based scaling exists at all scales.
- Large scales impose global mass entrainment.
- Small (viscous) scales adapt and do the job!

$\nabla p$ suggests that TNTI and RRI mean local fluxes might interact.
Perspectives

✓ Further test TBL-based scaling of mass entrainment
  ▶ $\delta/h$
  ▶ Free stream turbulence
  ▶ Basic control/perturbation

✓ Extend s.b.s. analysis
  ▶ RRI (no Fourier spectra!)
  ▶ Evolution along mean TNTI (no Fourier spectra!)
  ▶ Increase dynamic range: new (large) scales?

✓ What input for separation control systems?
✓ What input for enhanced numerical simulations?
Thank you for your attention!