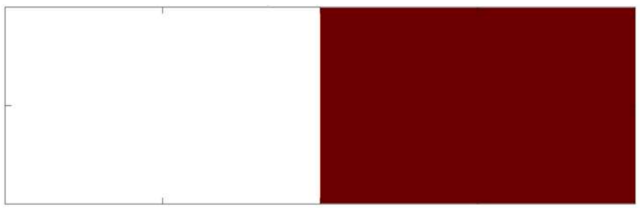
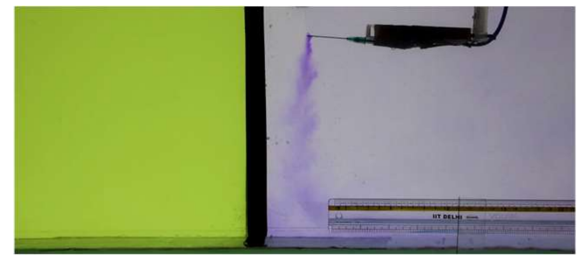
Role of fluid transport on sealing effectiveness of air curtains





PhD Defense

Tanmay Agrawal

2020AMZ8681

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External Expert: Prof. Krishnakant Agrawal

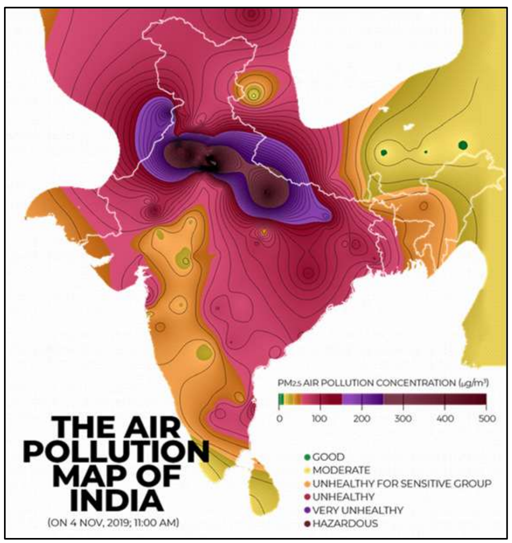
Outline

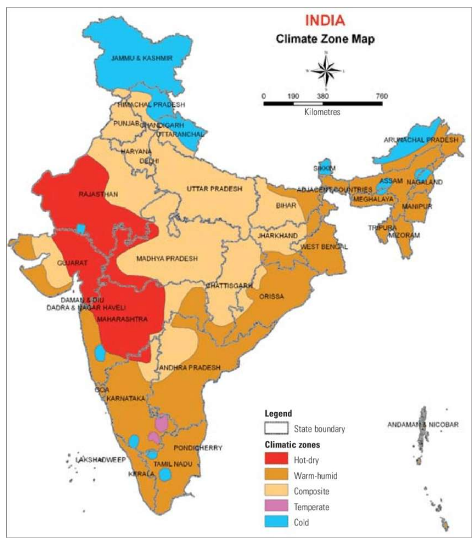
- Introduction: Building flows and the need of air curtains
- Parameter space
- Research questions
- Methodology
  - Numerical simulations
    - RANS
    - LES
  - Experiments
    - Bulk fluid transport
    - Velocity measurement
- Results
- Conclusions & future work

Building flows

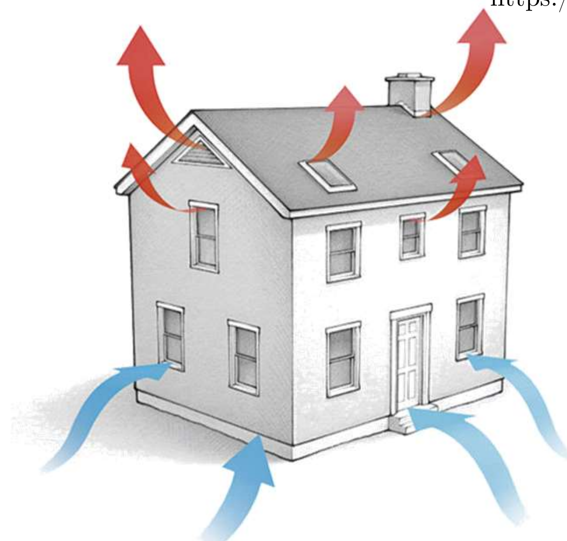
https://www.finehomebuilding.com

- Typical requirements of building occupants:
  - Thermal comfort
  - Air quality
  - Energy consumption





Source: Forbes India



Flow through doorways

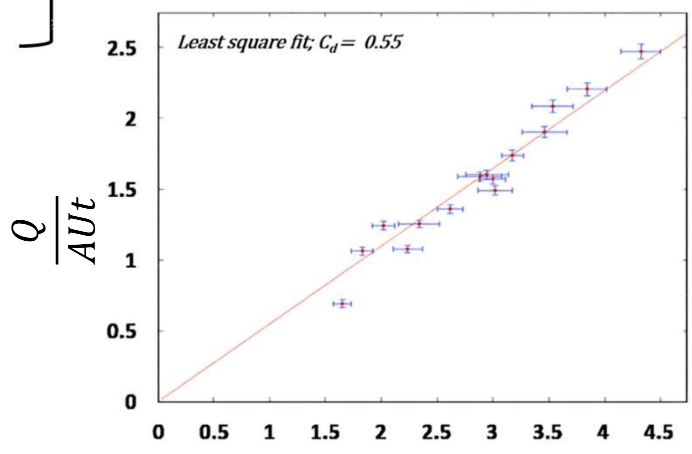
Velocity scale: $U = \sqrt{g'h}$

Reduced gravity: $g' = g\dfrac{\Delta\rho}{\rho_0}$

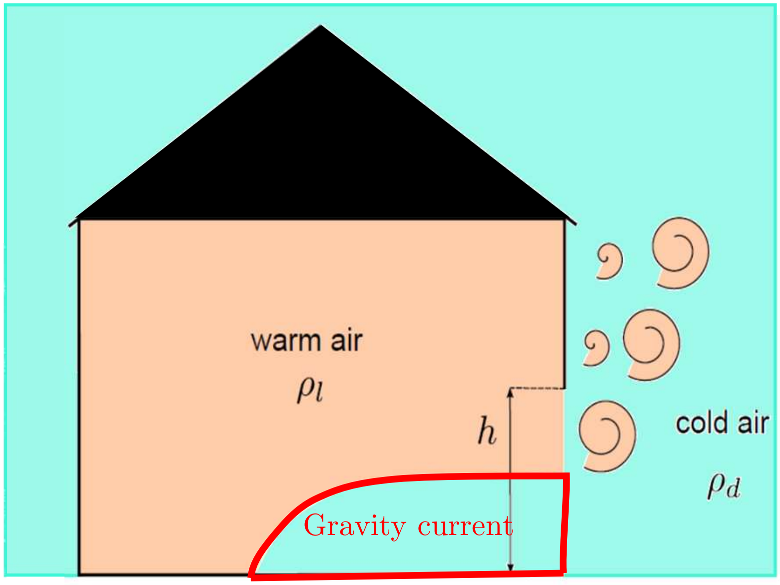
For $\Delta T = 15℃$ and $h = 2$ m

$U \approx 1$ m/s

Exchange flow: $Q = \dfrac{C_D}{3}AU$



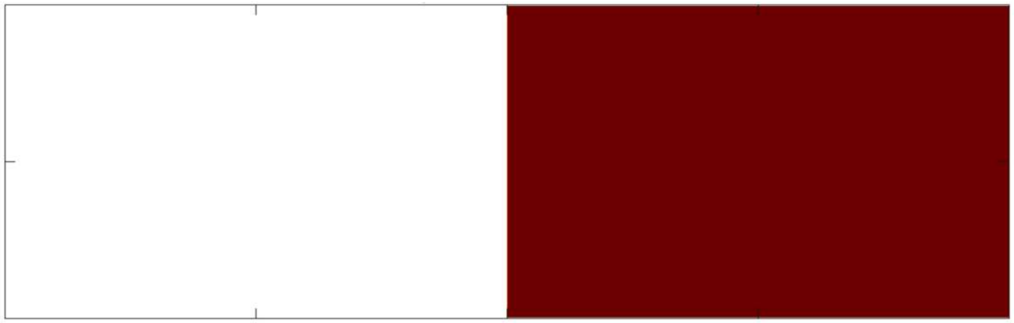
Non-dimensional time



Snacks outlet, Janpath

- Regular pedestrian and equipment movement
- Larger load on the HVAC systems.

How to suppress this exchange?



- Heat
- Pollutants
- Contaminants
- Insects

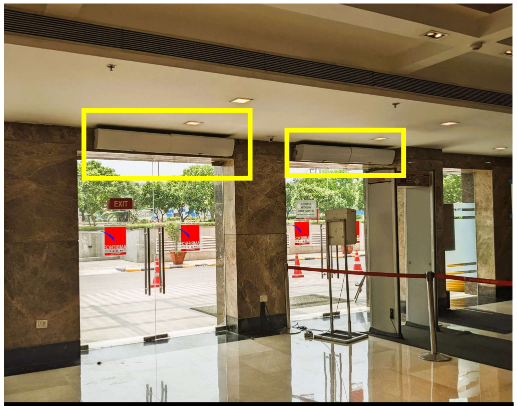
Chronology:

Conception and early works
- •Van Kennel (1904)
- •Hayes & Stoecker (1960s)
- •Howell & Shibata (1980)

Experiments
- •Guyonnaud *et al.* (2000)
- •Foster *et al.* (2006)
- •Frank & Linden (2014, 2015)

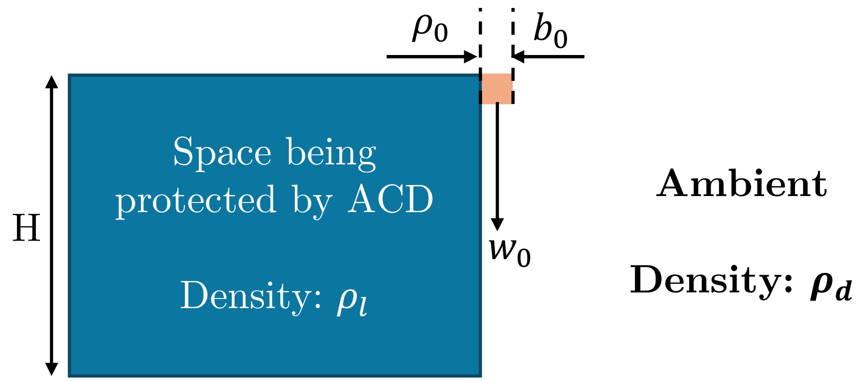
Simulations
- •Gonçalves *et al.* (2012)
- •Khayrullina et al. (2020)
- •Ruiz *et al.* (2021)

Café, SDA Market



Hauz Khas Metro Station

Flow characterisation: parameter space



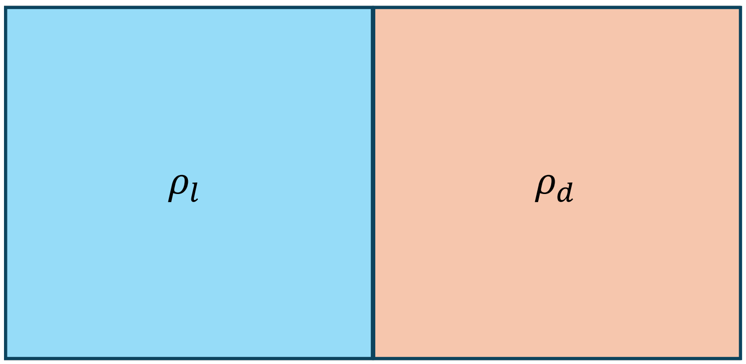
Hayes & Stoecker (1969):

Deflection modulus: $$D_m = \frac{Jet\ momentum\ flux}{Transverse\ \ force} = \frac{\rho_o b_o w_0^2}{gH^2\Delta\rho} \begin{cases} 0 \text{ (Gravity current)} \\ \infty \text{ (Non-buoyant jet)} \end{cases}$$

Other possible dimensionless candidate:

Froude number: $Fr_0 = \frac{w_0}{\sqrt{g' b_0}}$

Cases studied

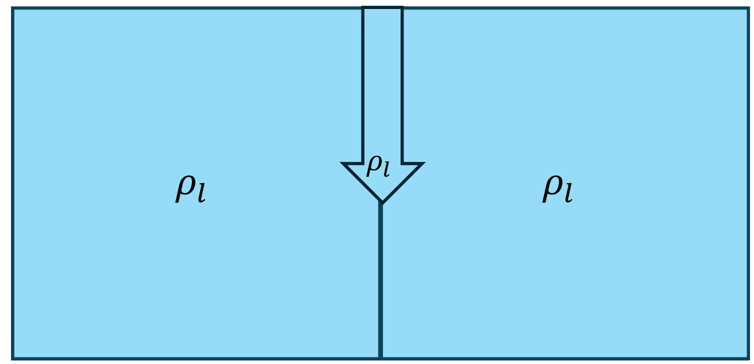


Case I: Lock-exchange (GC)

$\rho_l < \rho_d$

Experiments (E)
- ✓ Dye vis.
- ✓ Density
- ✓ PIV

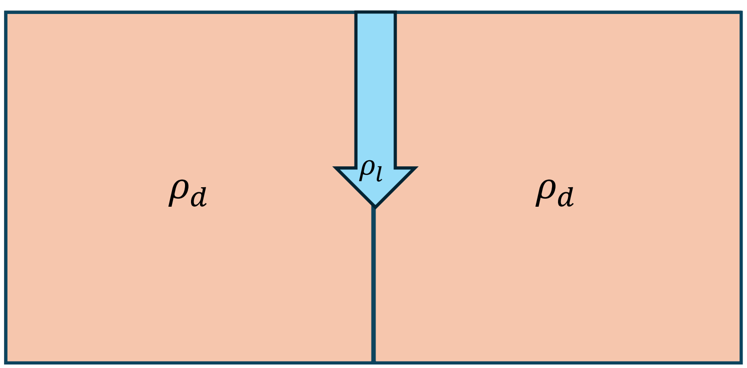
Simulations (S)
- ✓ RANS
- ✓ LES



Case II: Non-buoyant jet (NBJ)

$\rho_0 = \rho_l = \rho_d$

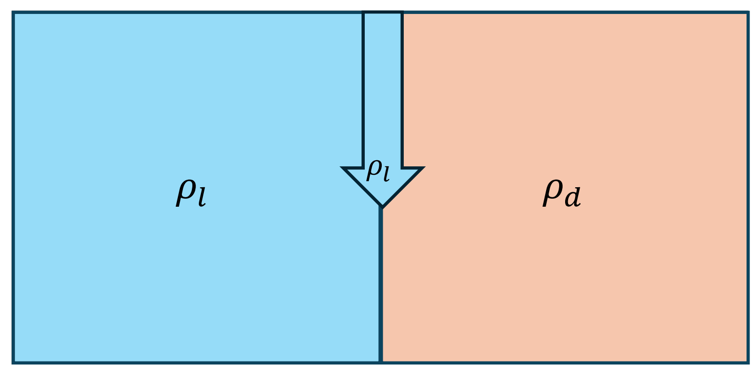
Re
1000 (E)
1000 (S)
2500 (S)
4000 (S)



Case III: Forced Fountain (FF)

$\rho_0 < \rho_l = \rho_d$

Fr_0
14 (E,S)
21 (E,S)
28 (E,S)
40 (E,S)

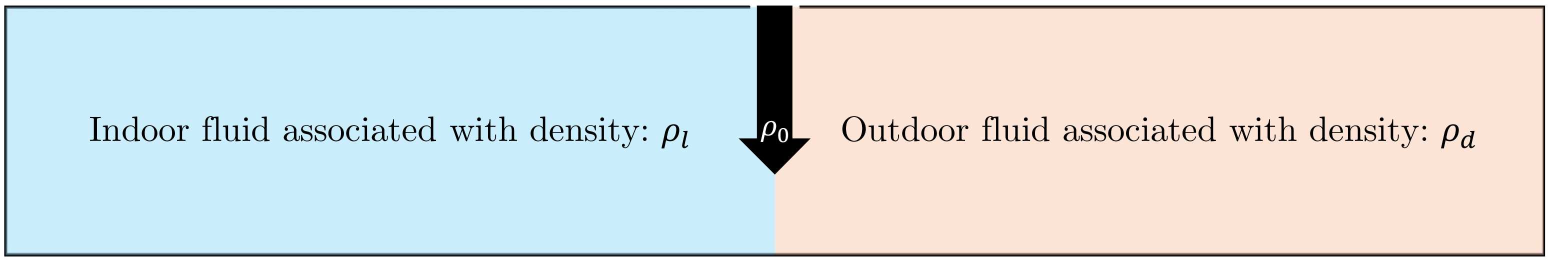


Case IV: Air curtain (AC)

$\rho_0 = \rho_l < \rho_d$

D_m
0.05 (S)
0.1 (E,S)
0.2 (E,S)
0.4 (E,S)
0.6 (E,S)
0.8 (E,S)
1.2 (E,S)
1.5 (S)

Fluid dynamics problem & Research questions



“Turbulent line fountain ⟷ lateral buoyancy field”

Bulk fluid transport:

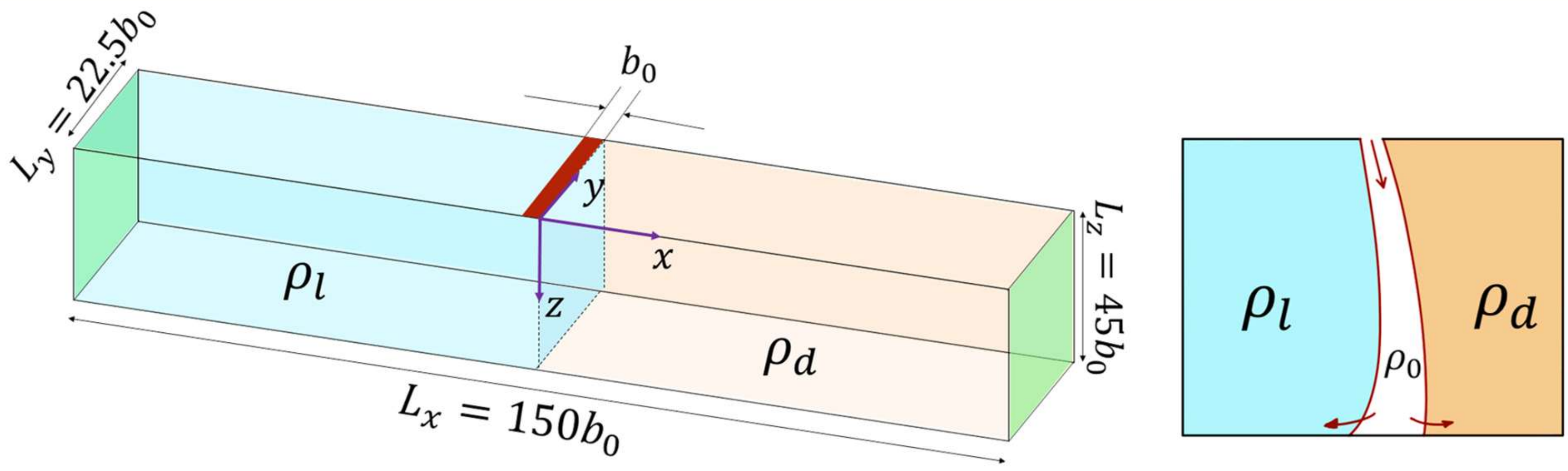
1. Outdoor fluid penetration
2. Transport mechanisms

Structure and entrainment:

3. Self-similarity considerations
4. Entrainment characteristics

Bulk fluid transport

Numerical setup and grid convergence



(a) (b)

Methodology	Grid points	N_{ACD}	Δy	Δz
RANS	261,600 (R3M1)	7	b_0	b_0
	422,400 (R3M2)	10	b_0	$0.7b_0$
	800,280 (R3M3)	15	$0.7b_0$	$0.5b_0$
LES	2,097,152 (L3M1)	12	$1.25b_0$	$0.62b_0$
	8,388,608 (L3M2)	12	$0.62b_0$	$0.31b_0$
	16,777,216 (L3M3)	24	$0.62b_0$	$0.31b_0$

Cases for grid independence: Isothermal jet, lock-exchange flow.
10 (D_m) X 4 grids = 40 simulations

Governing equations: RANS

$$u = \underbrace{U}_{\text{mean}} + \underbrace{u'}_{\text{fluctuation}}$$

Unclosed system of equations:

Mass:
$$\frac{\partial U_i}{\partial x_i} = 0$$

Momentum:
$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i' u_j'}\right] - g[1 - \beta(T - T_0)]\delta_{13}$$

Energy:
$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\kappa \frac{\partial T}{\partial x_j} - \overline{u_j' T'}\right]$$

Turbulence closure (RNG $k-\epsilon$ model)

TKE:
$$\frac{\partial k}{\partial t} + U_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + \mathcal{P}_k + \mathcal{B}_k - \epsilon$$

Dissipation rate:
$$\frac{\partial \epsilon}{\partial t} + U_i \frac{\partial \epsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \epsilon}{\partial x_i}\right] + \frac{\epsilon}{k}\left(C_{1\epsilon}\mathcal{P}_k + C_{1\epsilon}(1 - C_{3\epsilon})\mathcal{B}_k - C_{2\epsilon}^* \epsilon\right)$$

Governing equations: LES

- Filtered equations under Boussinesq approximation

Continuity: $$\frac{\partial \overline{u_i}}{\partial x_i} = 0$$

Momentum: $$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial \overline{p}}{\partial x_i} - \overline{b}\,\delta_{i3} + \frac{\partial}{\partial x_j}\left[\nu\frac{\partial \overline{u_i}}{\partial x_j} - \tau_{ij}^R\right]$$

Buoyancy: $$\frac{\partial \overline{b}}{\partial t} + \overline{u_j}\frac{\partial \overline{b}}{\partial x_j} = \kappa_b\frac{\partial}{\partial x_j}\left[\frac{\partial \overline{b}}{\partial x_j} - \lambda_{ij}^R\right]$$

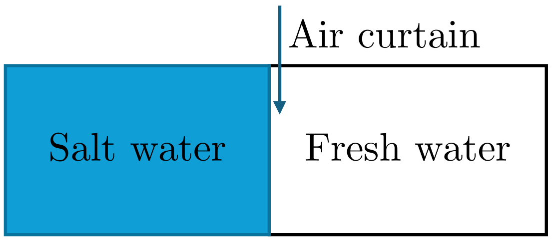
- Subgrid stresses modeling:

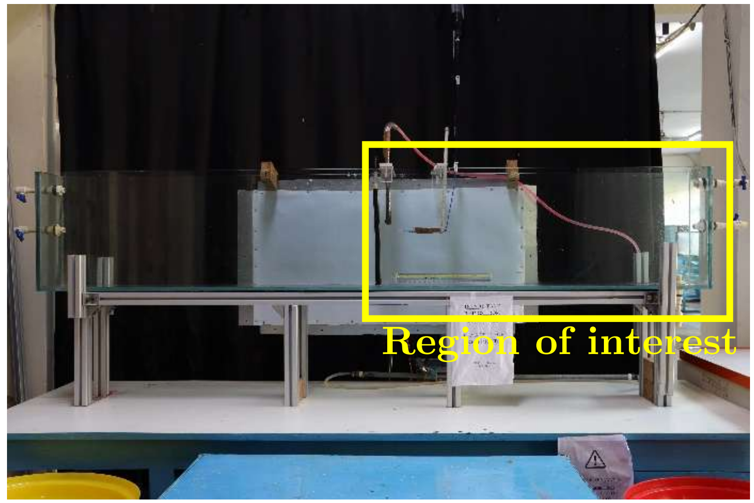
$$\tau_{ij}^R - \frac{1}{3}\tau_{kk}^R\delta_{ij} = -2\nu_{sgs}\overline{S}_{ij}$$

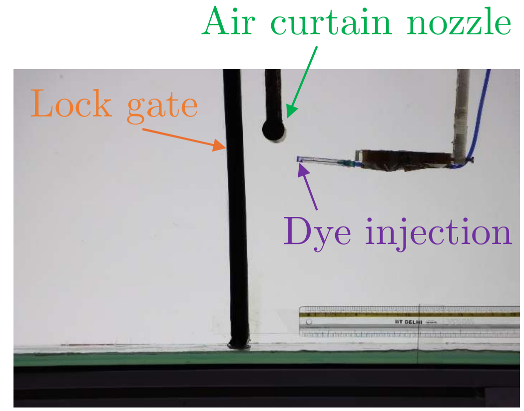
$$\lambda^R = -2\kappa_{sgs}\frac{\partial \overline{b}}{\partial x_j}$$

- Solver: **S**tratified **O**cean **M**odel with **A**daptive **R**efinement (SOMAR).
  - Second-order FDM for spatial derivatives
  - RK method for time advancement.

Experiments

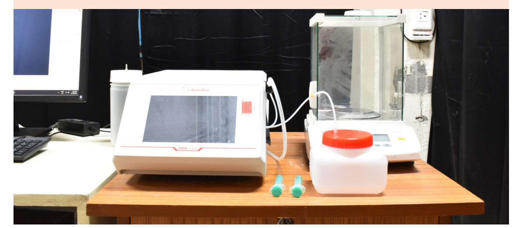






Camera's FOV for flow visualization
Canon EOS90D – 100 Hz, F/5.6

Density measurement system



Typical experimental workflow:

1. Install the lock and fill the tank on both sides simultaneously
2. Density samples from both sides to quantify initial configuration
3. Establishment of air curtain (lock gate closed)
4. Lock release to allow fluid transport across the air curtain
5. Lock re-installment followed by switching off the air curtain
6. Density samples from both sides to quantify fluid exchange

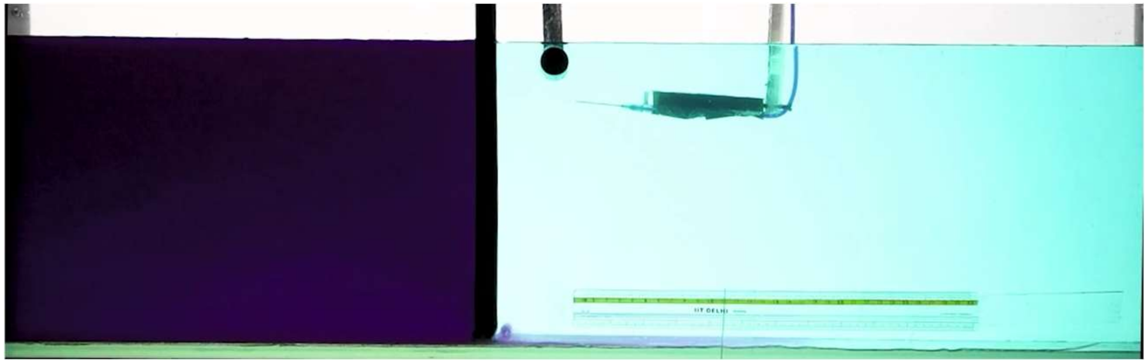
Anton Paar DMA1001
Accuracy: ± 0.0001 gm/cc

Rockwin Turbine FM
± 1% of measured value.

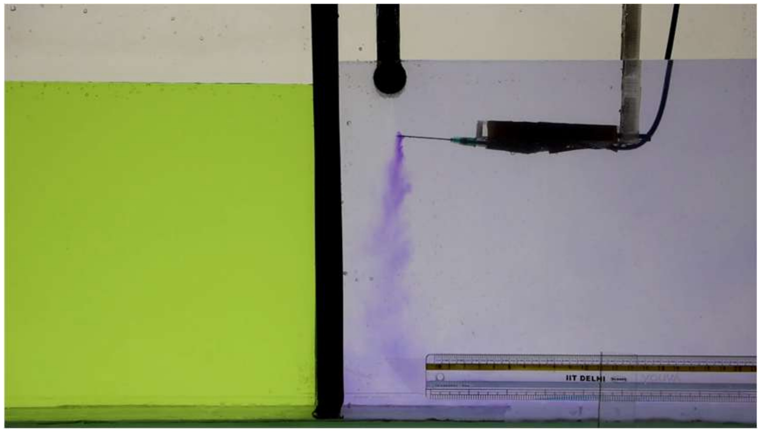
20 experiments spanning the range of D_m

Dye visualisation

- **Base case:** lock-exchange resulting in the generation of *gravity current.*



Stable air curtain installation ($\boldsymbol{D_m \gtrsim 0.2}$)



Unstable air curtain ($\boldsymbol{D_m \lesssim 0.1}$)

Data reduction (Fluid exchange)

- Mass conservation in the dense fluid half:

$$\rho_d^n(V + V_{ACD}) = \rho_d V \underbrace{- \rho_d V_{ex} + \rho_l V_{ex}}_{\text{Mass exchange from the dense side to light}} + \underbrace{\rho_0 V_{ACD}}_{\text{Mass added by the air curtain}}$$

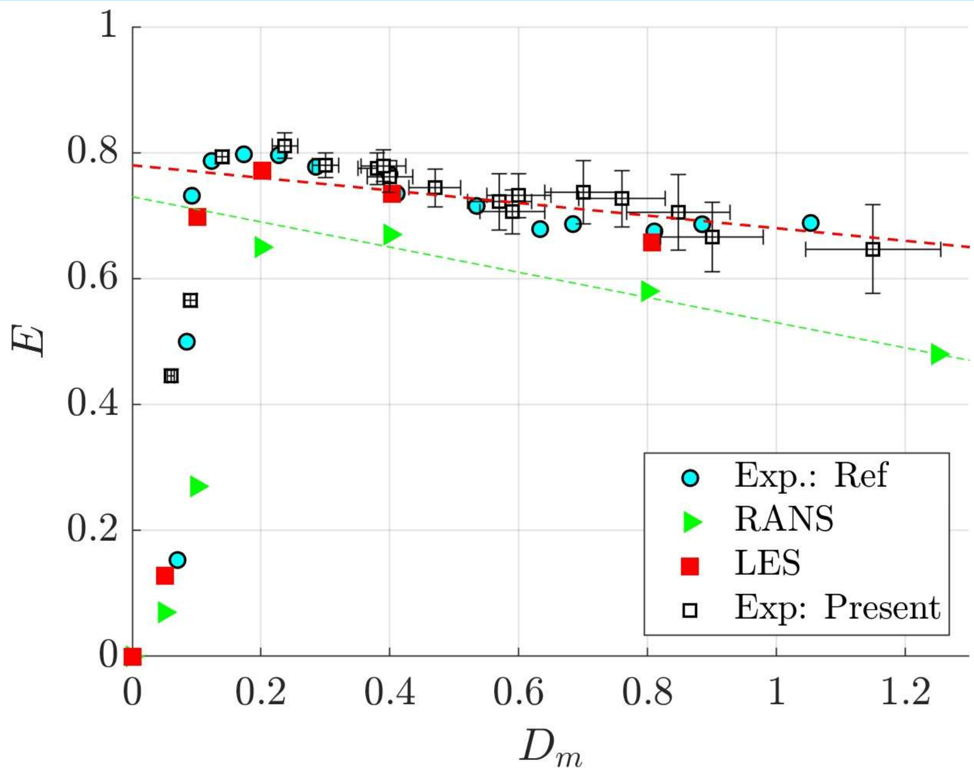
- Exchange flow rate:

$$q_{ACD} = \frac{V_{ex}}{t_{ex}} = \left(\frac{\rho_d - \rho_d^n}{\rho_d - \rho_l}\right)\left(\frac{V + V_{ACD}}{t_{ex}}\right)$$

- Sealing effectiveness:

$$E = \frac{q - q_{ACD}}{q} = 1 - \frac{q_{ACD}}{q}$$

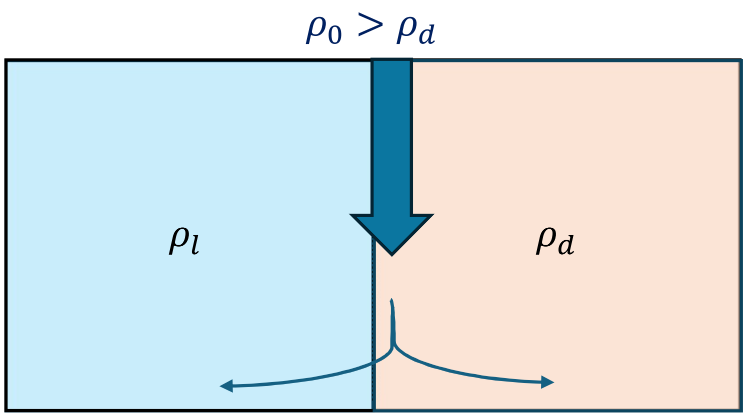
Air curtain effectiveness



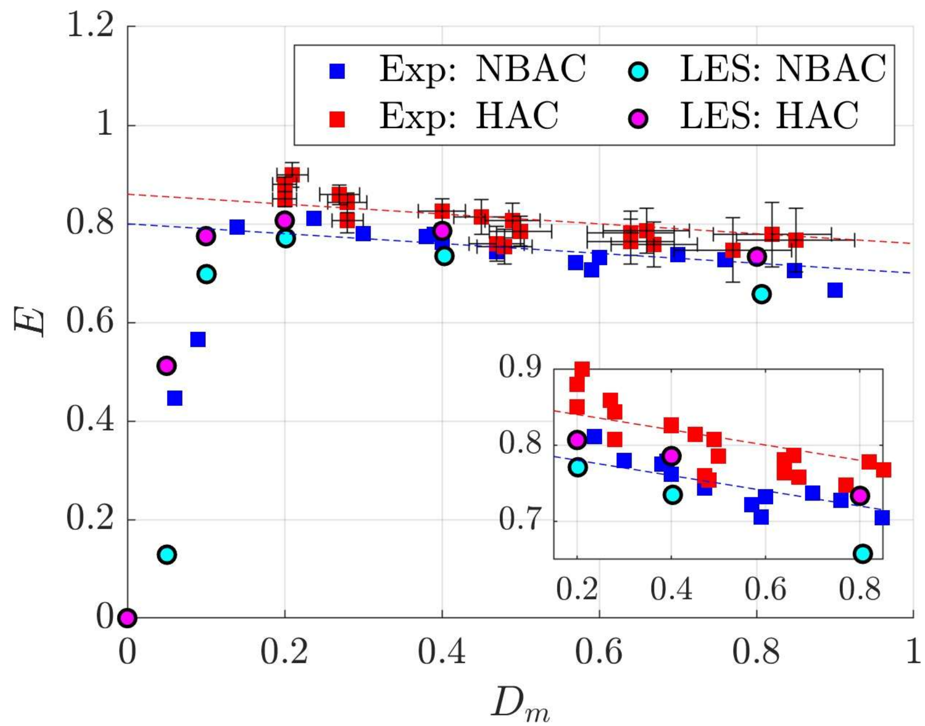
- RANS predictions: consistently smaller.
- LES: very good overlap with the experimental data.

[Ref.] NK. Jha, D. Frank, L. Darracq, and PF. Linden. *Energy and Buildings* (2021)

Influence of assistive buoyancy (Heavy air curtain)



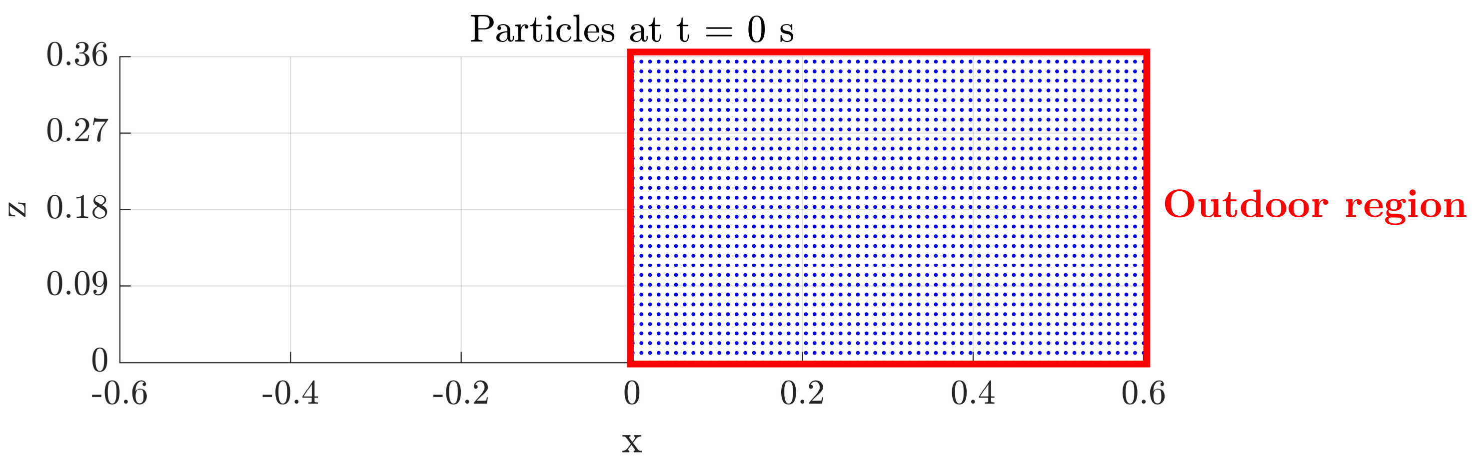
$S = \dfrac{\rho_0 - \rho_d}{\rho_d - \rho_l}$	D_m
Experiments: 0.3	0.20
	0.30
Simulations: RANS: 0.17, 0.30, 0.39. LES: 0.3	0.45
	0.65
	0.75



- Fluid infiltration in HAC: upto 25% lesser.
- Effectiveness increases as the assistive buoyancy increases.

How does the fluid transport occur?

Lagrangian framework analysis

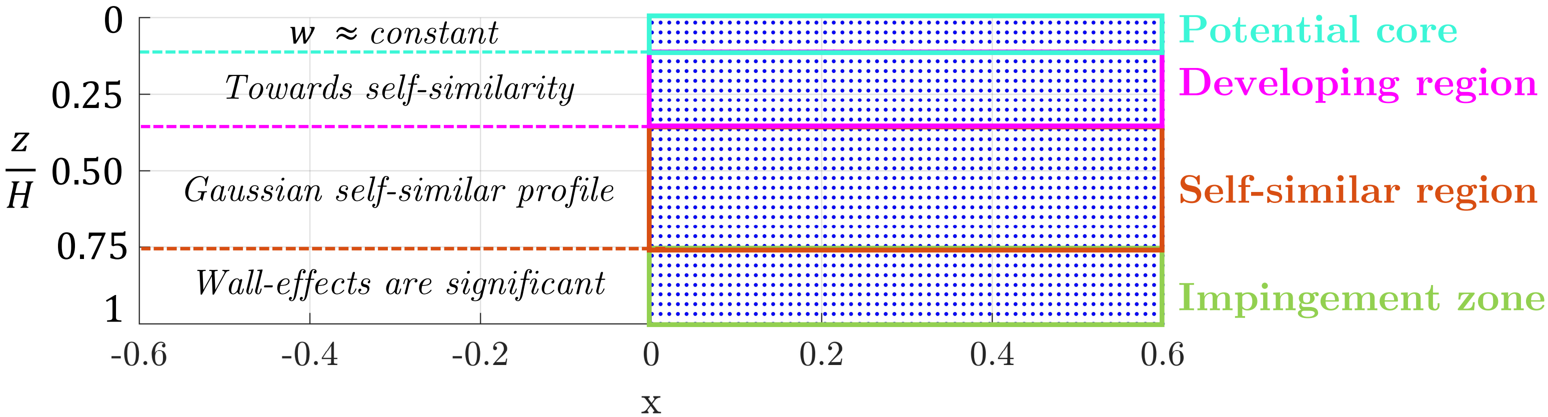


Fluid particles evolve according to: $$\frac{dx_p}{dt} = \boldsymbol{u}(x_p, t)$$

1. Transport to the indoor region ($\boldsymbol{x} < \boldsymbol{0}$)?
2. Where do they come from?
3. Physical mechanisms?

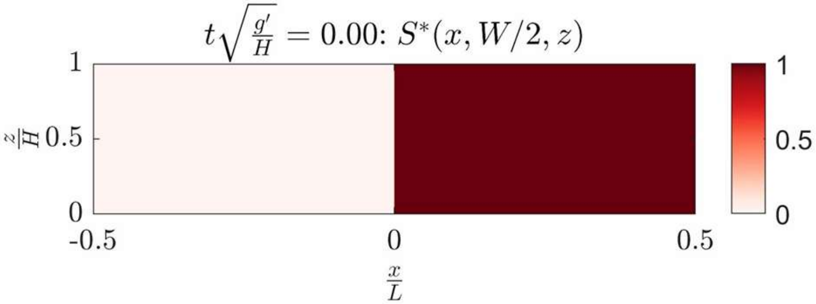
Crossing fraction: $$X_f(t) = \frac{n_{in}^t}{N}$$

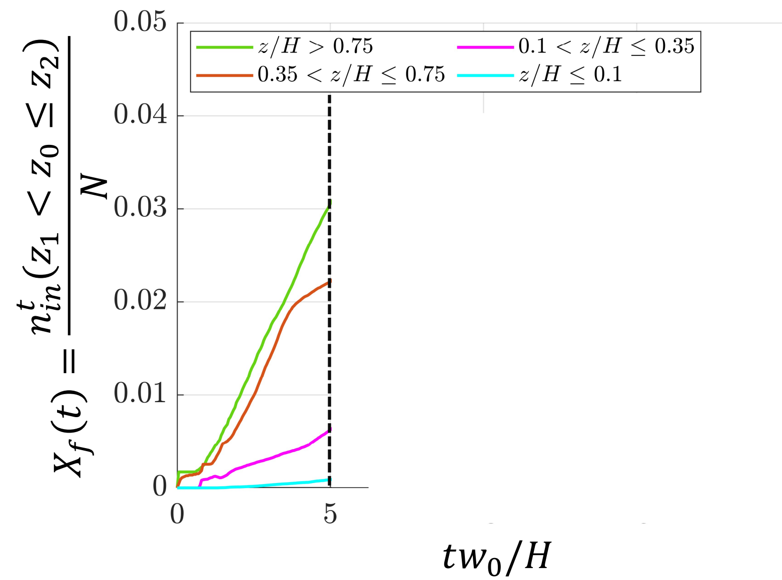
Origin of infiltrating fluid



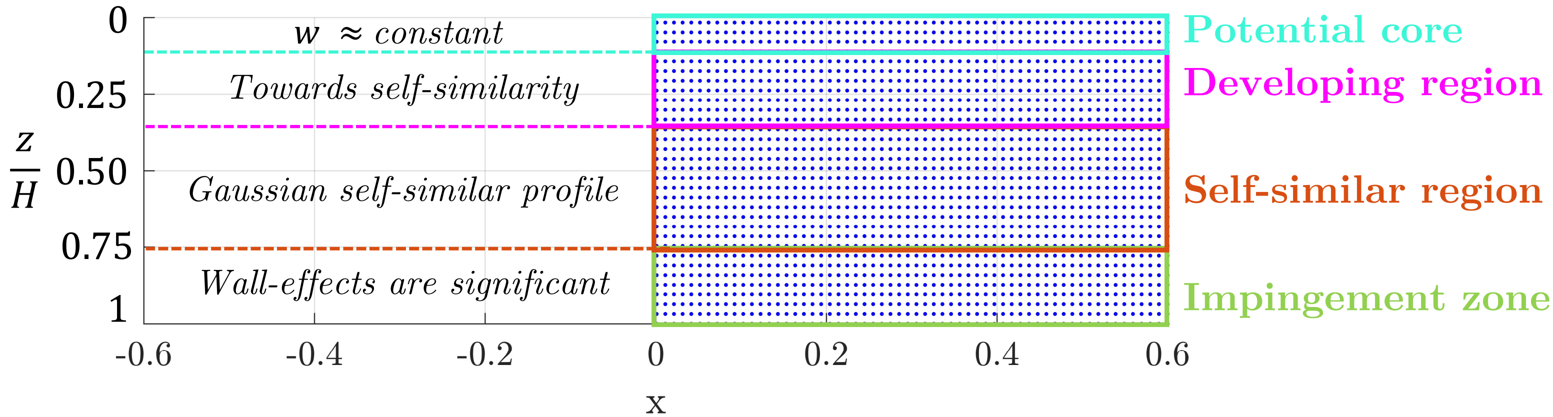
Initial time

$\frac{tw_0}{H} < 5$

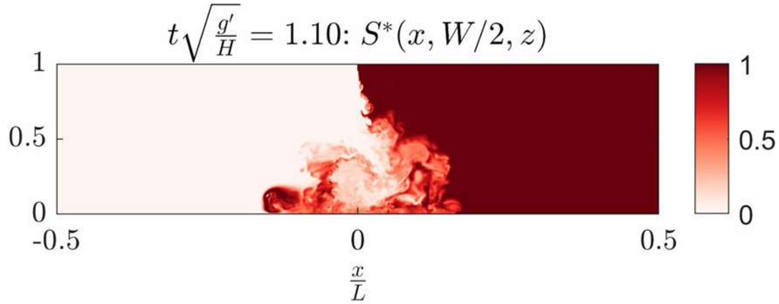


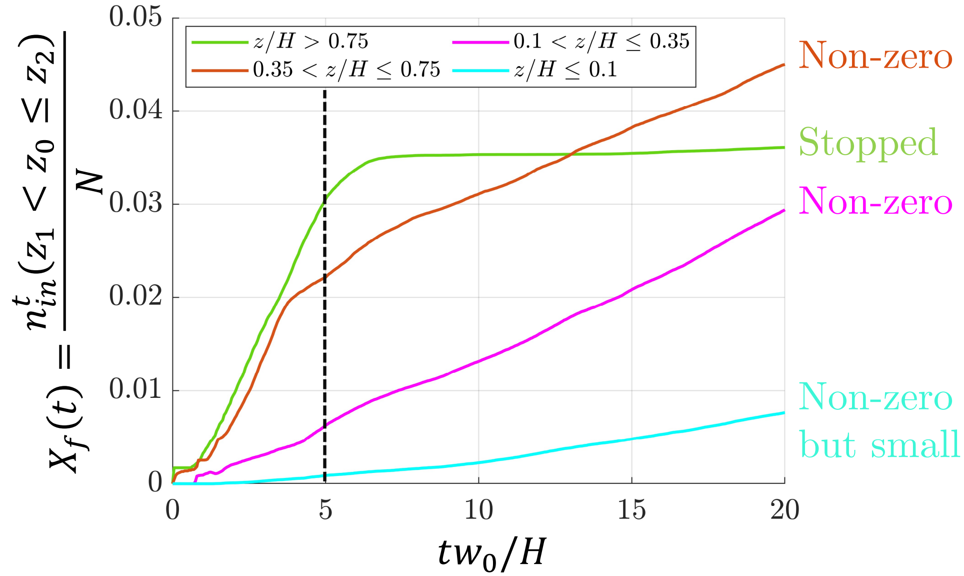


Origin of infiltrating fluid

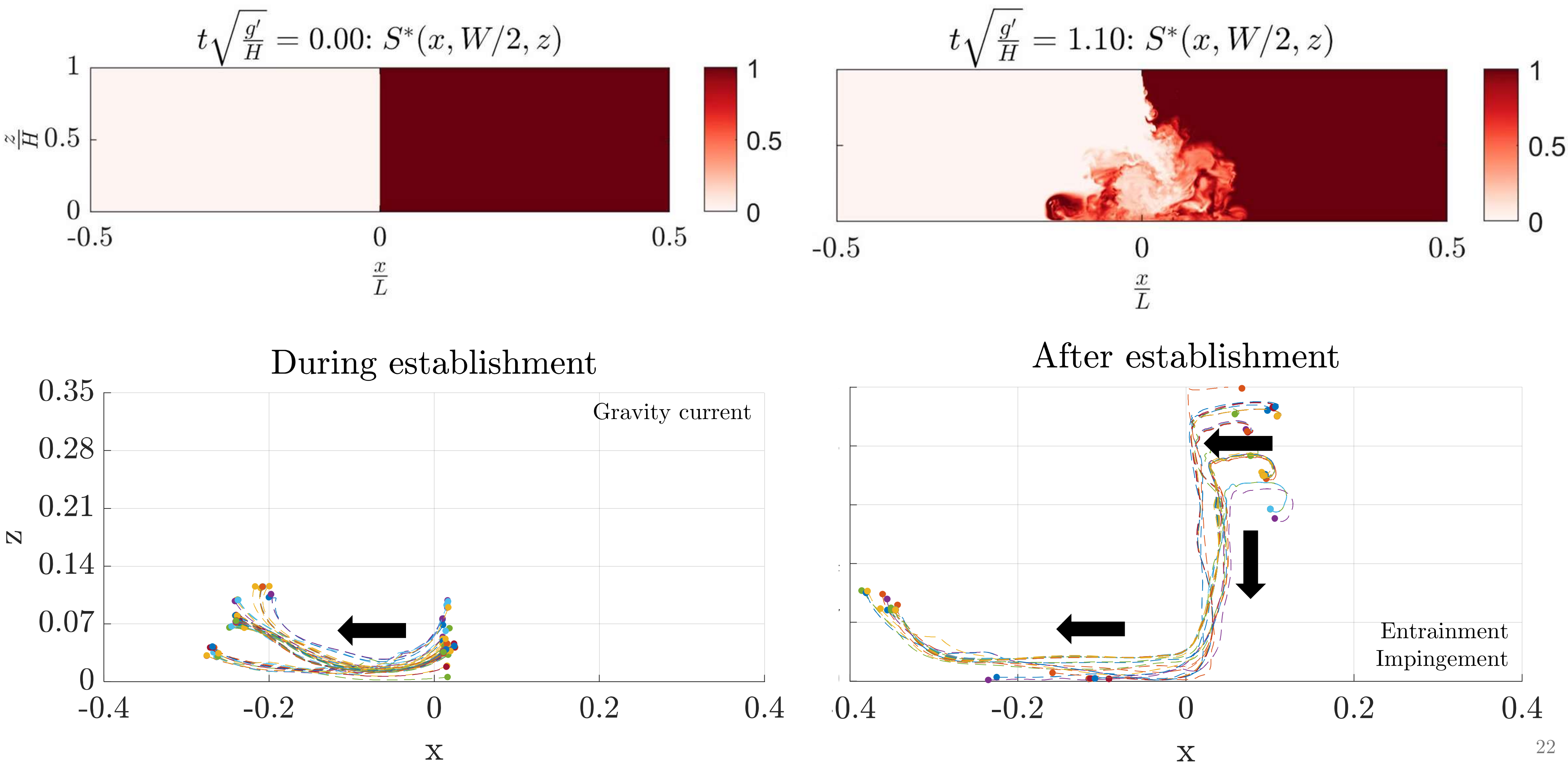


Later times

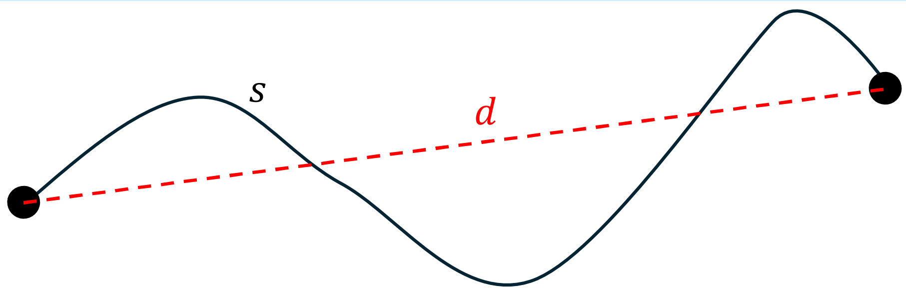




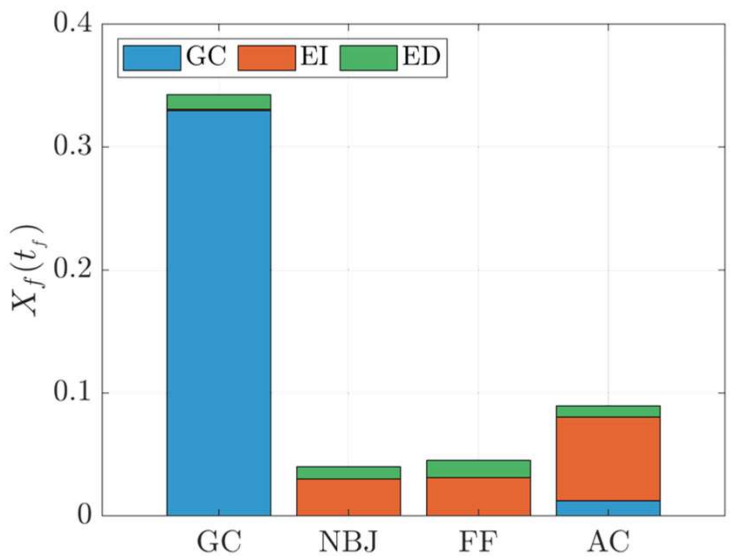
Insights into transport mechanisms



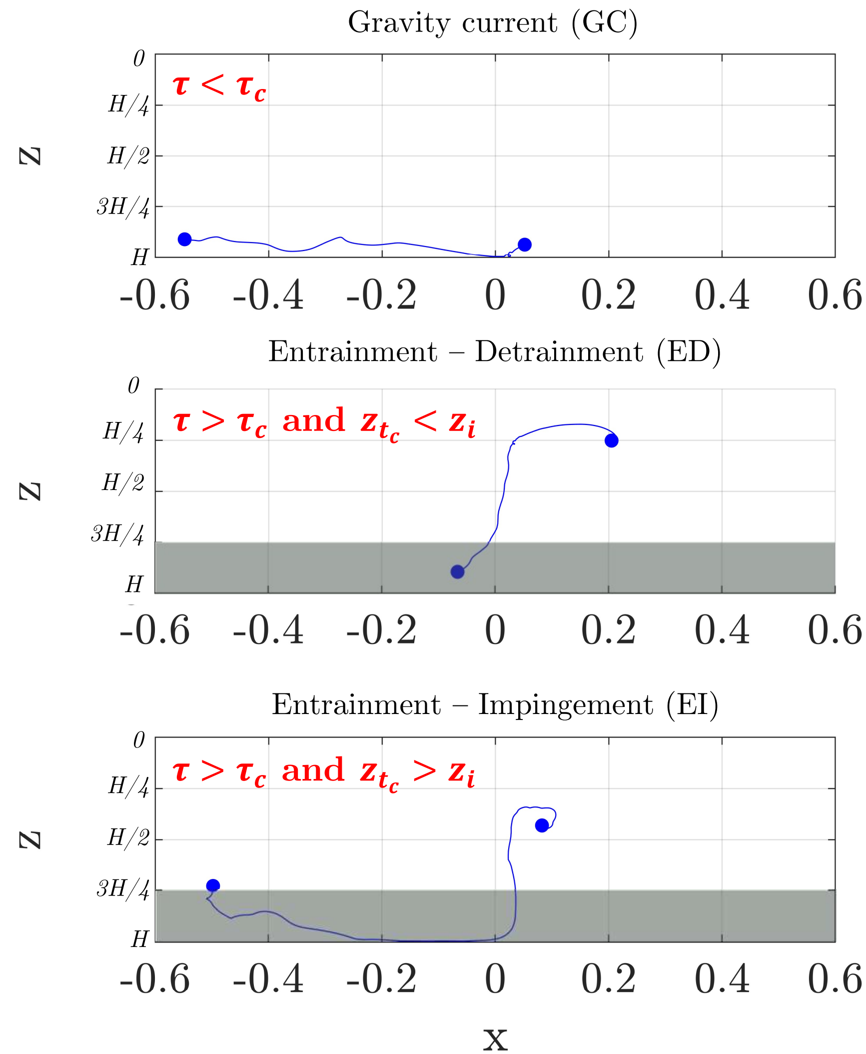
Quantification of transport mechanisms



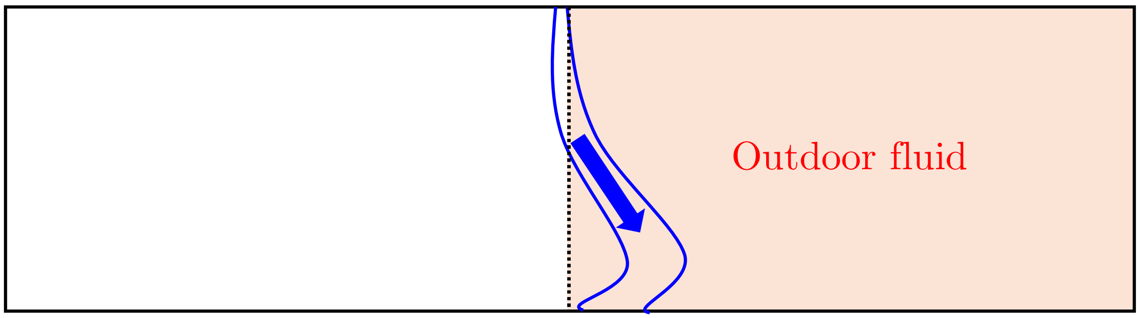
- Tortuosity, $\boldsymbol{\tau} = \dfrac{\text{Length of the trajectory}}{\text{Net displacement}} = \dfrac{s}{d}$
- The spatial location at the time of crossing ($\boldsymbol{z_{t_c}}$)



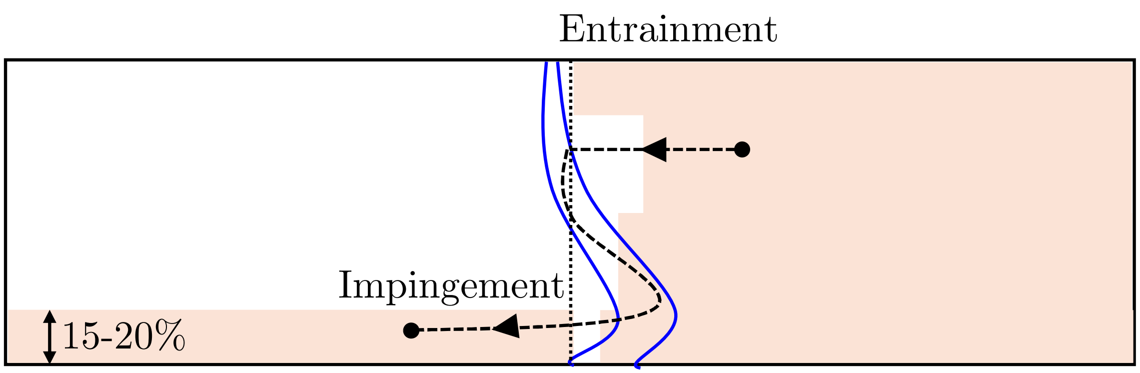
GC: Base case without an air curtain.
NBJ: Base case of non-buoyant jet.
FF: Fountain with no lateral density diff.
AC: Air curtain



In summary



- Minimum deflection modulus
- Resolution of large eddies

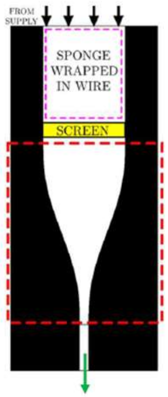


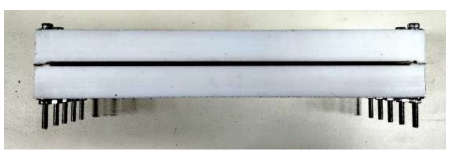
- Sealing ≠ 100%
- Near-wall suppression

Flow statistics

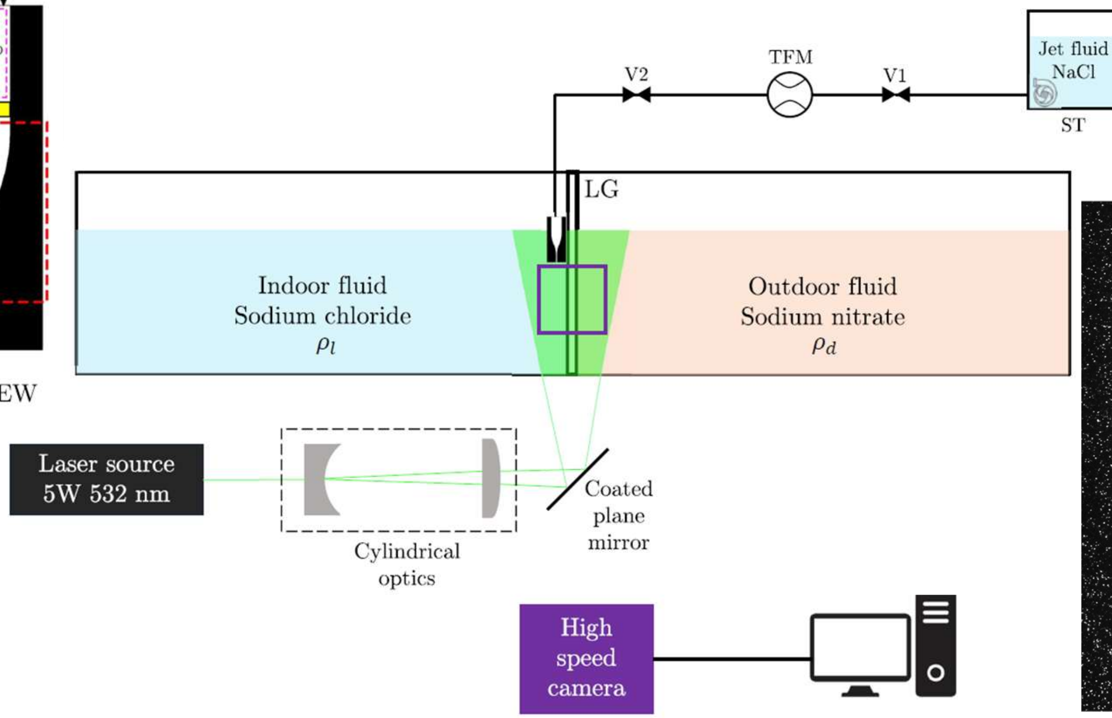
PIV measurements

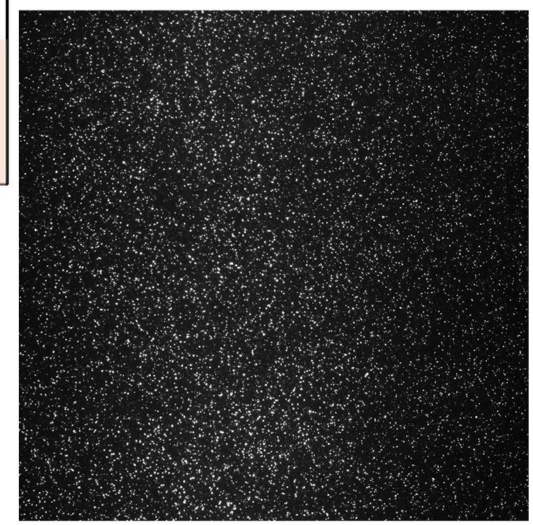
From
supply





Exit slot. 2 mm x 166 mm.

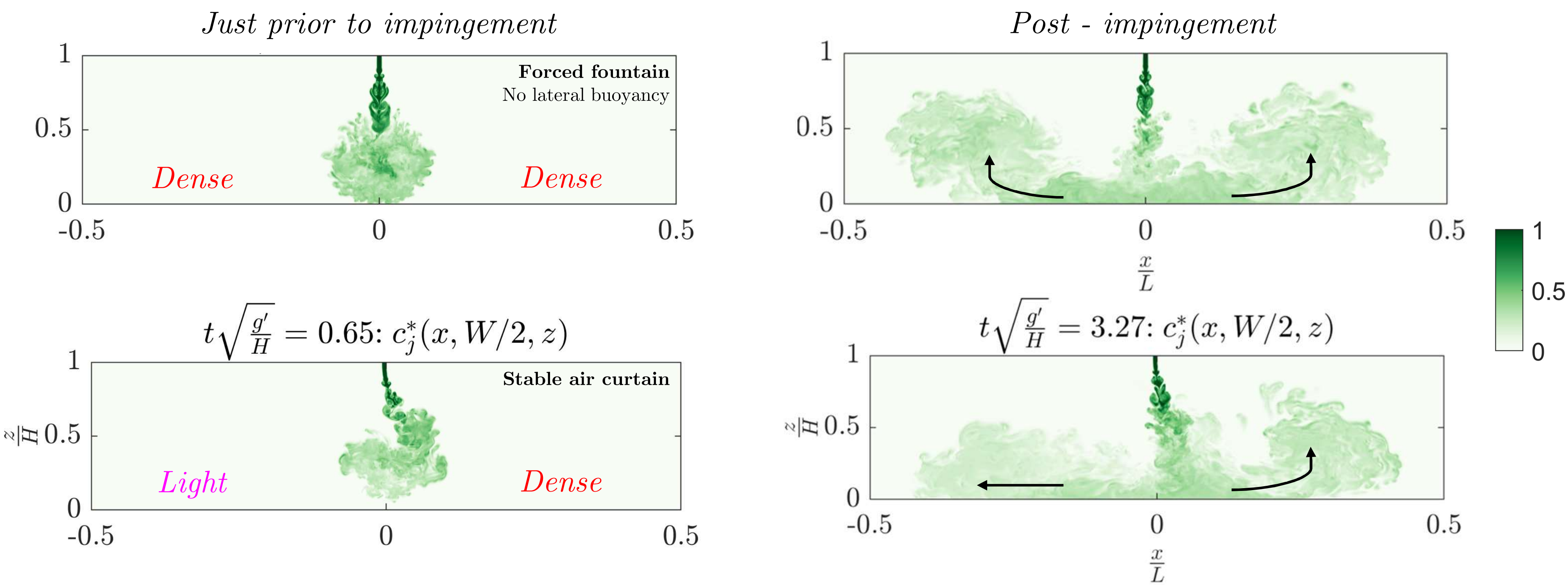




- Data acquisition: 500 Hz.
- Spatial resolution: 1.4 mm x 1.4 mm.
- 45 independent experimental runs.

Effect of lateral density difference: High Fr_0 or D_m

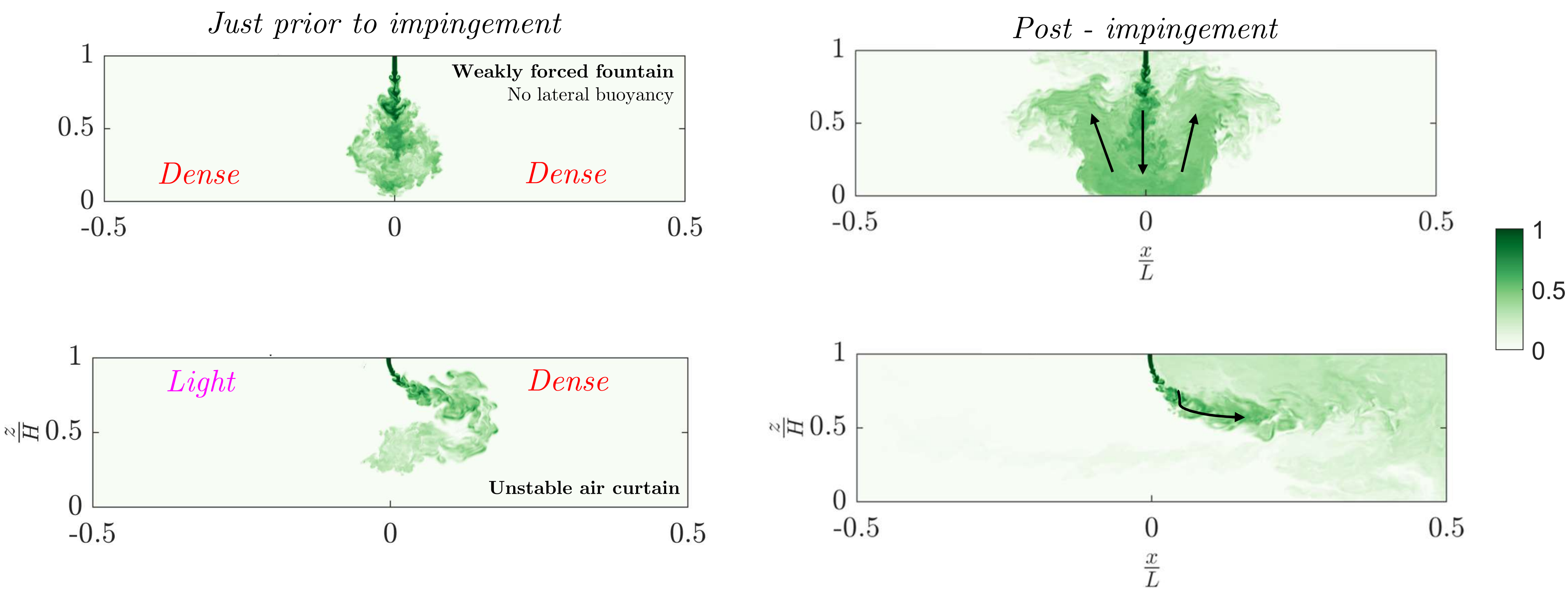
Flow development: fountain vs. air curtain.



Contours of passive tracer mixed with the source fluid

Effect of lateral density difference: Low Fr_0 or D_m

Increasing the density difference.



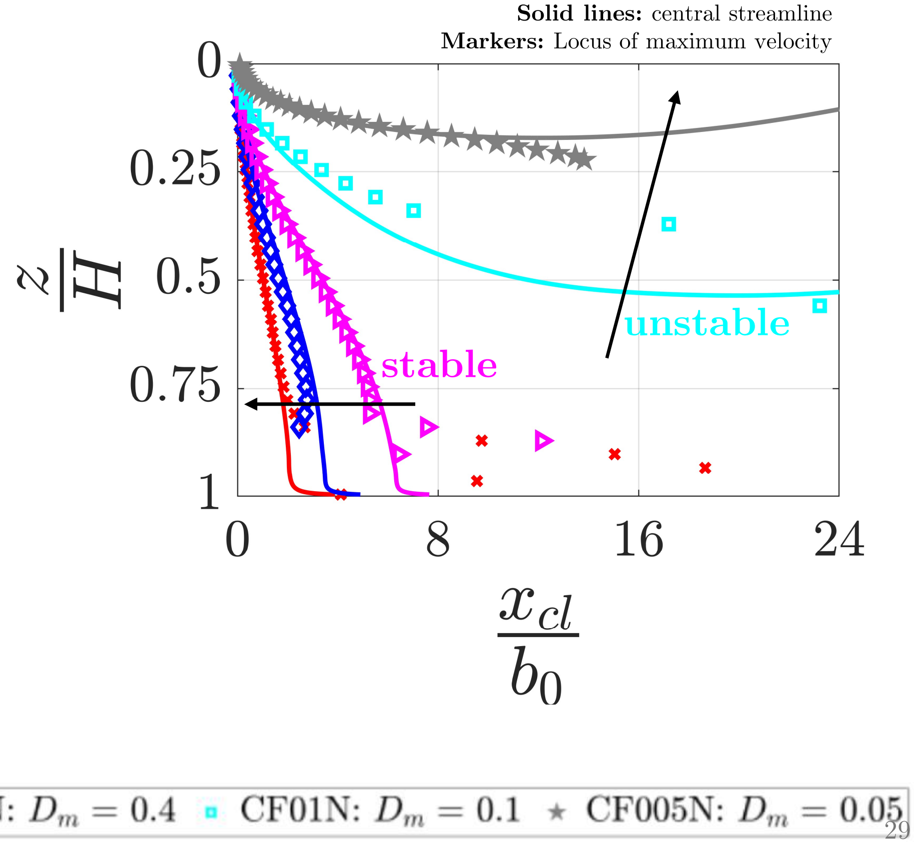
Contours of passive tracer mixed with the source fluid

Quantifying the lateral deflection of air curtains

- Spatiotemporal averaging:

$$\overline{w}(x,z) = \frac{\int_{T_1}^{T_2}\int_{Y_1}^{Y_2} w(x,y,z,t)\,dy\,dt}{(T_2-T_1)(Y_2-Y_1)}$$

- Centreline detection techniques:
  1. Velocity maxima
  2. Central streamline

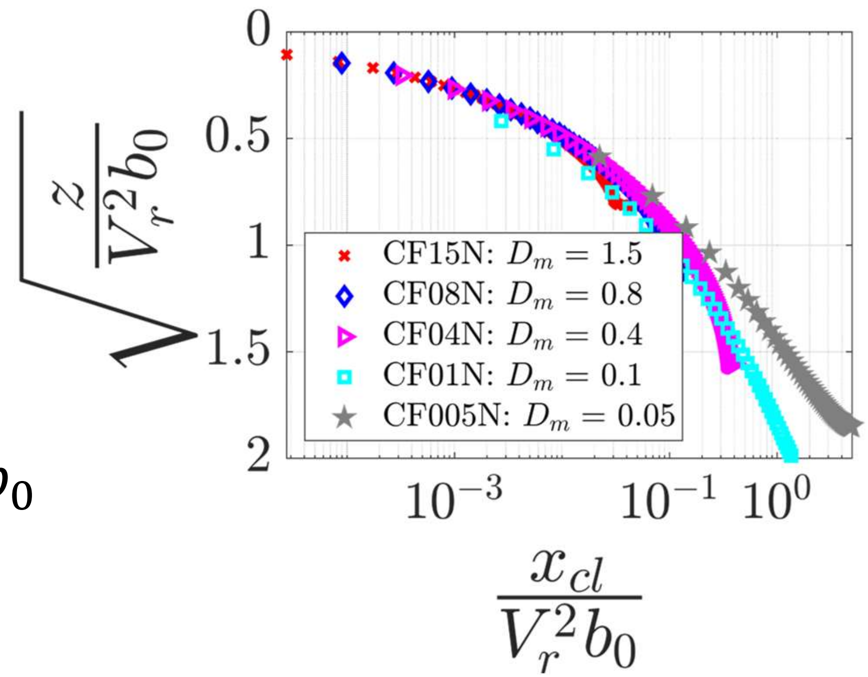


Scaling of lateral deflection

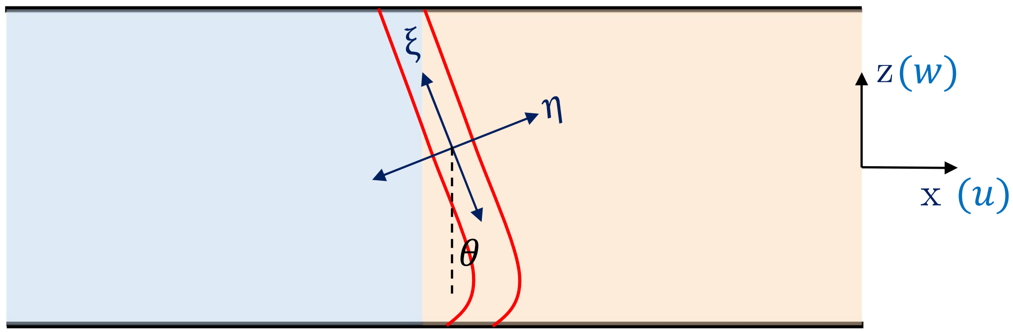
- Trajectory (x_{cl}) is influenced by:
  - Initial momentum flux: $M = w_0^2 b_0$
  - Ambient velocity: $v_b = \sqrt{g'H}$

- Through dimensional analysis:
  - $x_{cl} = f(z, M, v_b)$

- Momentum length scale: $L_m = \frac{M}{v_b^2} = V_r^2 b_0$
  - We get: $\frac{x_{cl}}{L_m} = f\left(\frac{z}{L_m}\right)^{\frac{1}{2}}$

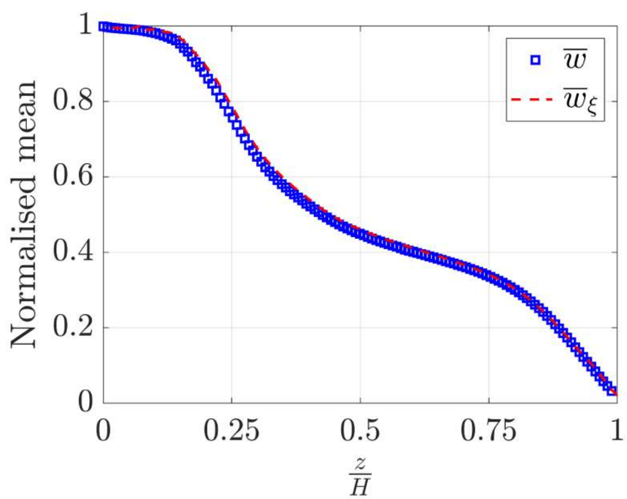


Velocity decomposition

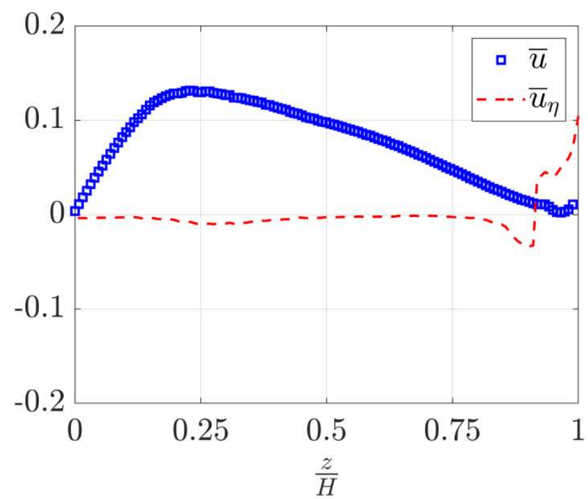


Streamwise velocity component, $w_\xi = w\cos\theta - u\sin\theta$

Streamnormal velocity component, $u_\eta = u\cos\theta + w\sin\theta$

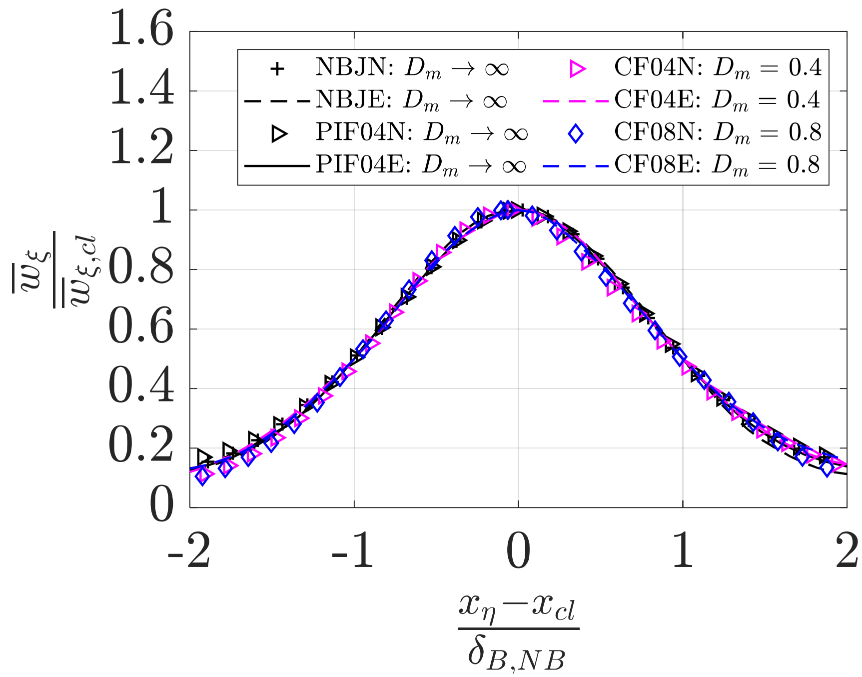


(a)



(b)

Self-similarity of mean velocity



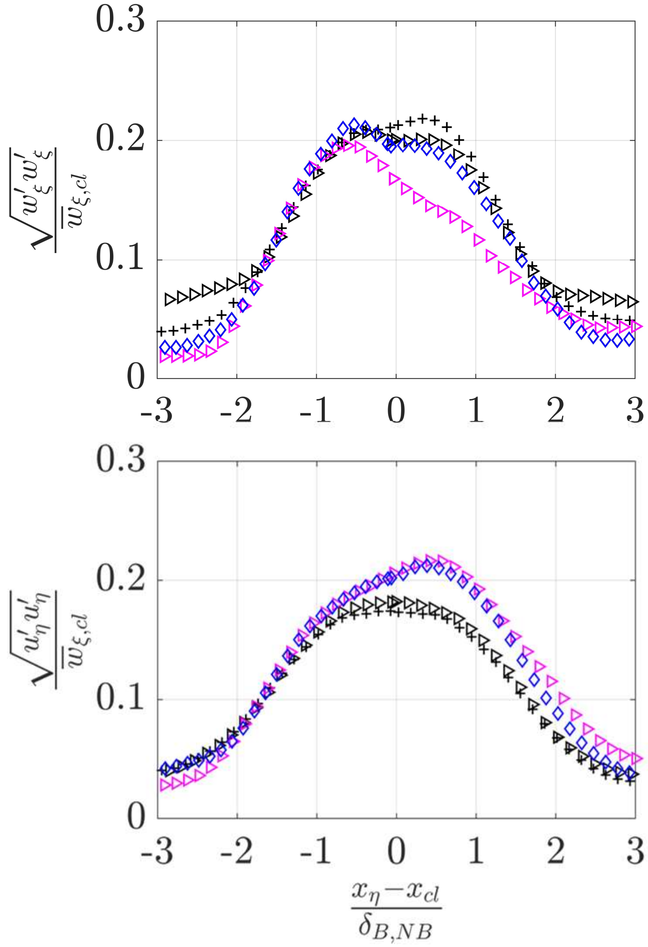
- Mean streamwise velocity → Gaussian and self-similar.

- Initial asymmetry in air curtain does not affect the Gaussian nature.

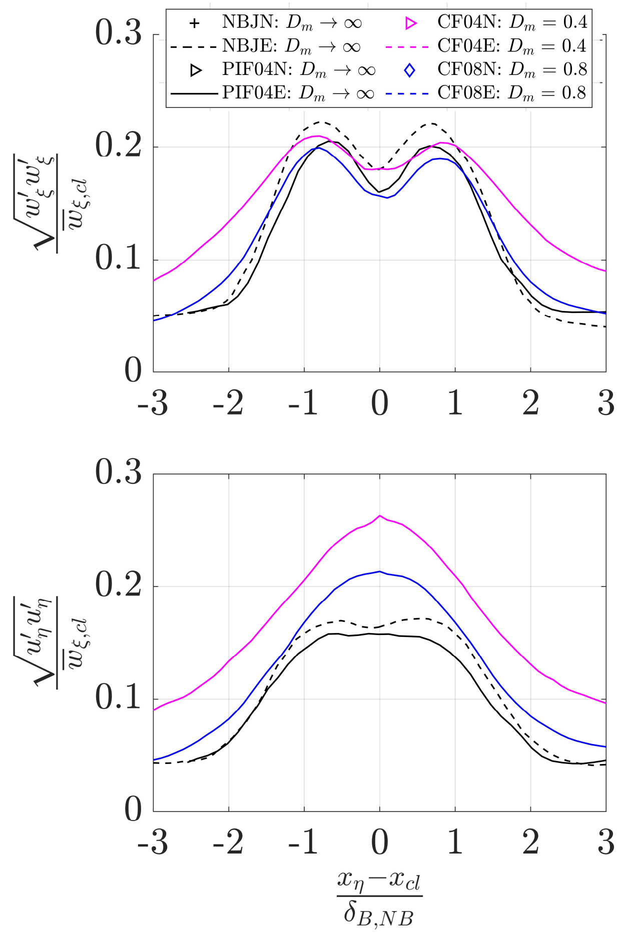
Turbulence statistics along stream-normal

Streamwise RMS

Stream normal RMS



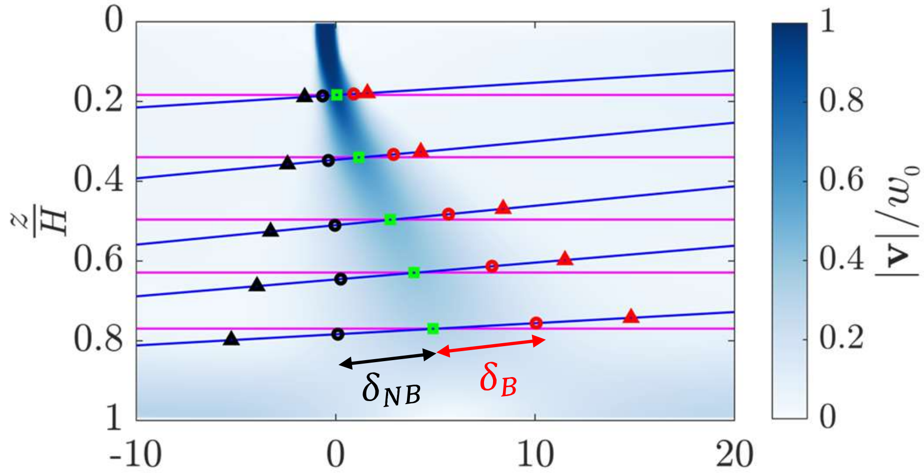
RMS profiles: Simulations

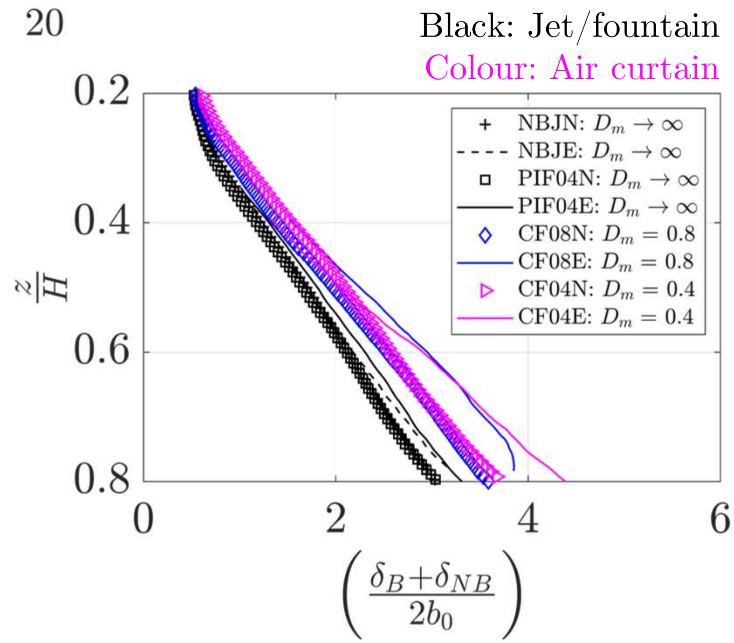


RMS profiles: Experiments

Cross-stream development: lateral spread

Circles:
Locations of half-width on buoyant (red) and non-buoyant (black) sides.
Triangles:
Twice the corresponding half-width location for edge.



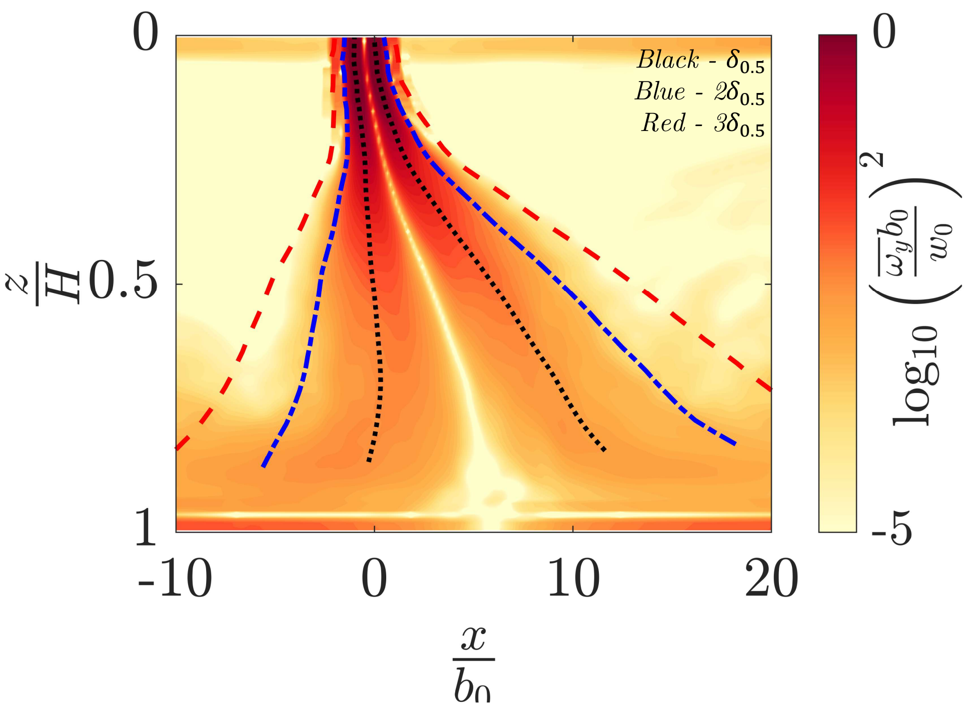


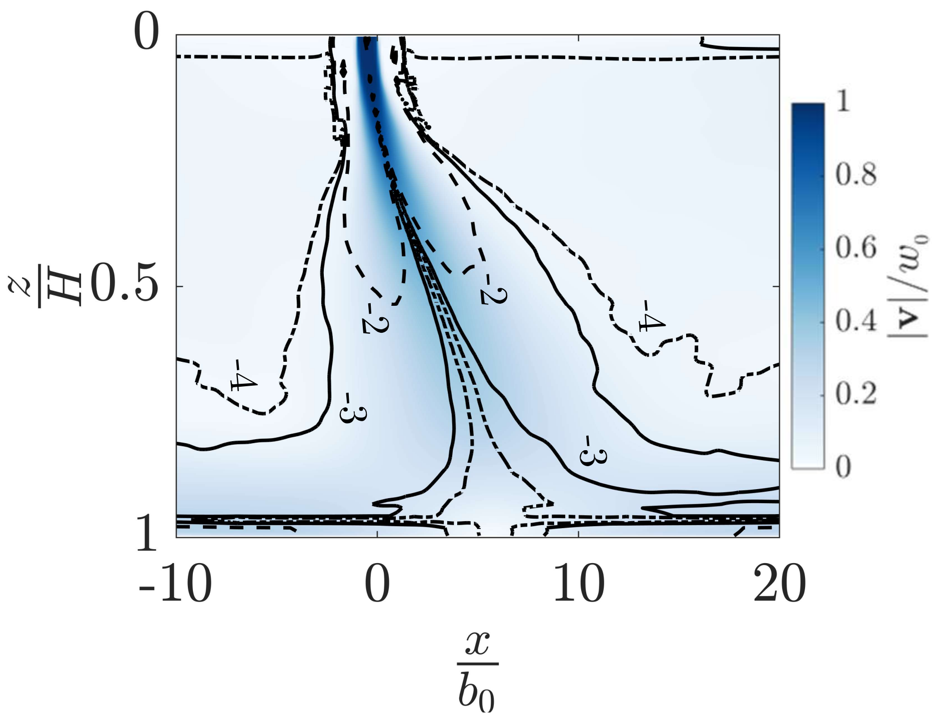
- Average halfwidth: larger in air curtains.
- Asymmetric development: $\delta_B > \delta_{NB}$

Entrainment characterization

Defining the jet/fountain edges

- Enstrophy distributions → segregating of turbulent fluid and relatively irrotational ambient.
- $2\delta_{0.5}$ is a suitable indicator of the edge.

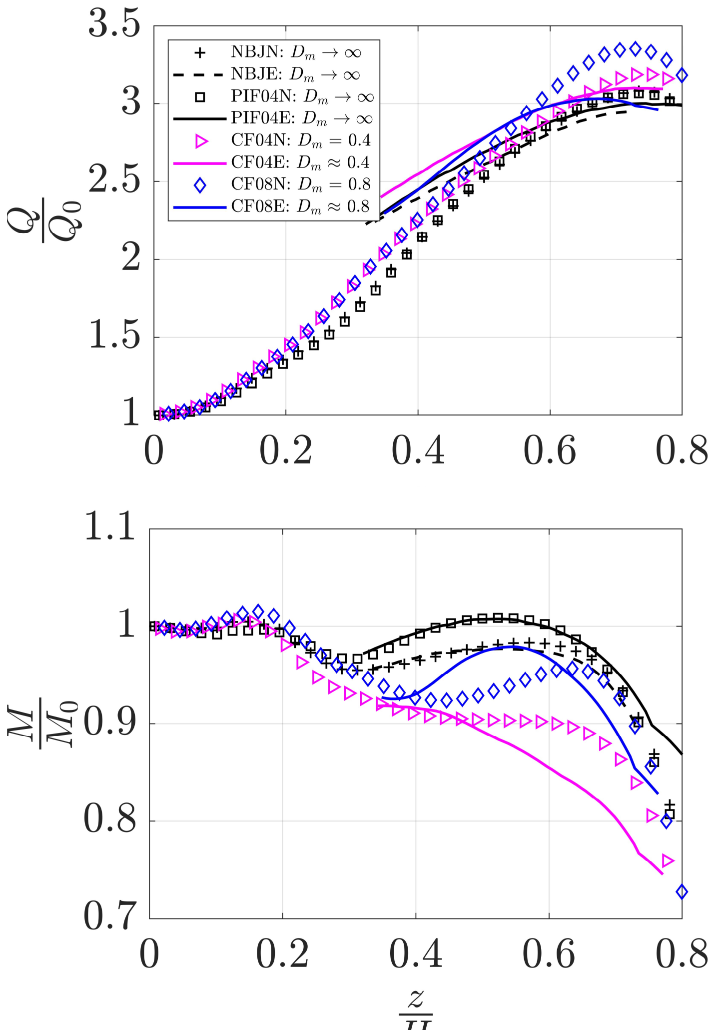




Integral fluxes

Integral volume flux: $Q = \int_{-\infty}^{\infty} \overline{w_\xi}\, d\eta$

Momentum flux: $M = \int_{-\infty}^{\infty} \overline{w_\xi}^2\, d\eta$

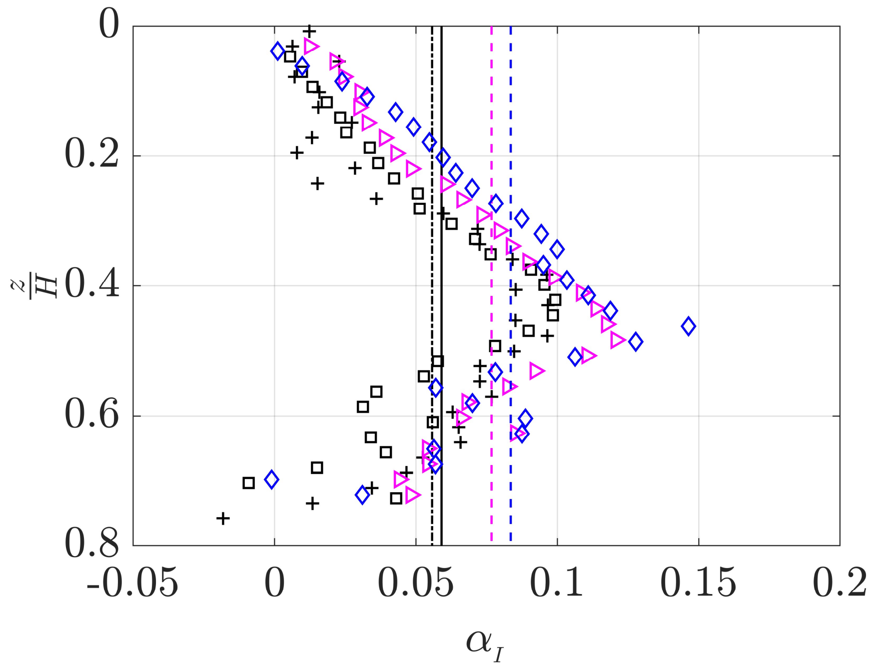


- **Volume flux**
  - Increases with a near constant slope
  - Decreases upon reaching closer to the wall.
- **Momentum flux**
  - Remains nearly constant for the jets and fountains.

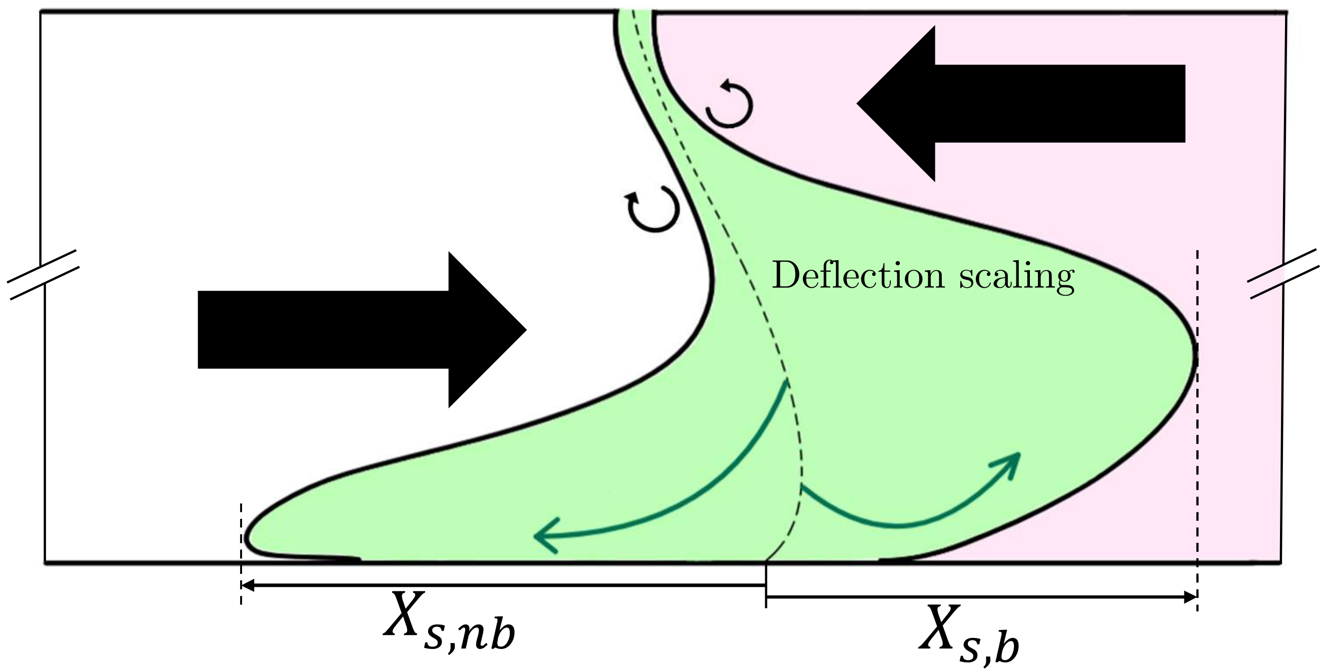
Integral entrainment coefficient

$$\frac{dQ}{dz} = 2\alpha_I \frac{M}{Q}$$

- α_I: air curtains > jets
- Lateral forcing *pushes* fluid into the core → higher fluid entrainment.



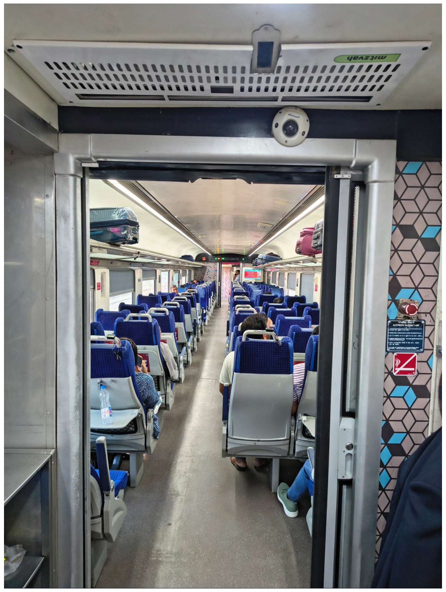
To summarize



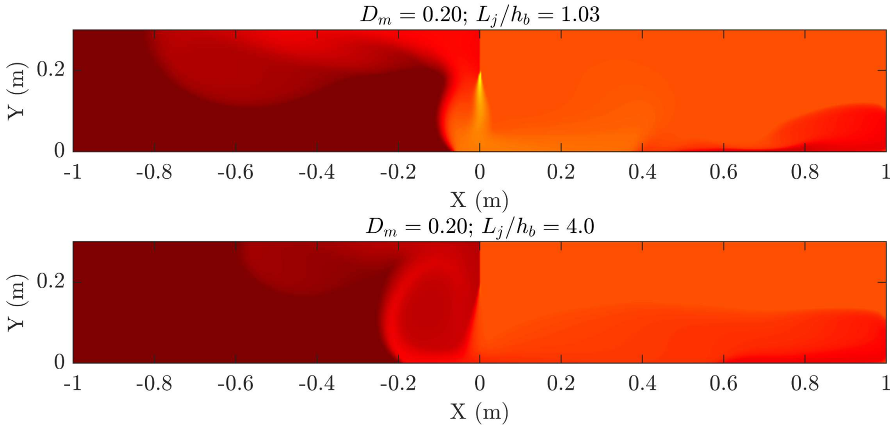
- Asymmetric spreading
- Self-similar mean profiles
  - Turbulence $\neq$ SS

- Lateral forcing key factor!
- Asymmetric entrainment

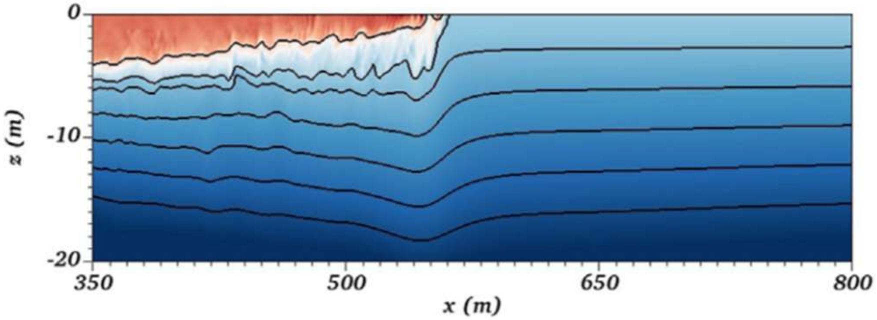
Snapshots of other research



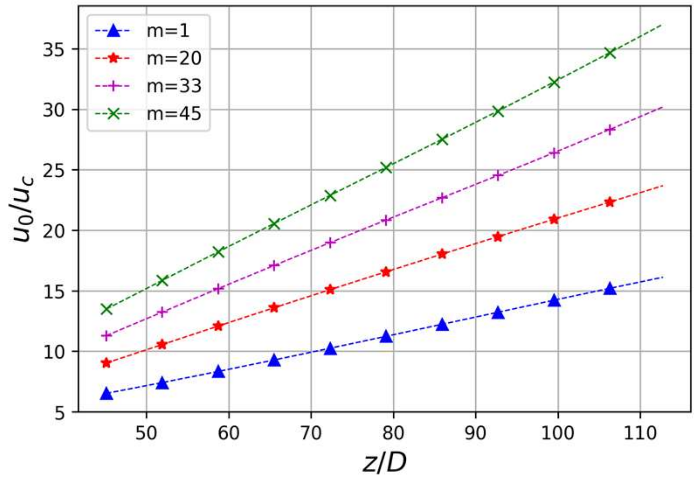
Air curtains in IR



Buoyant air curtains

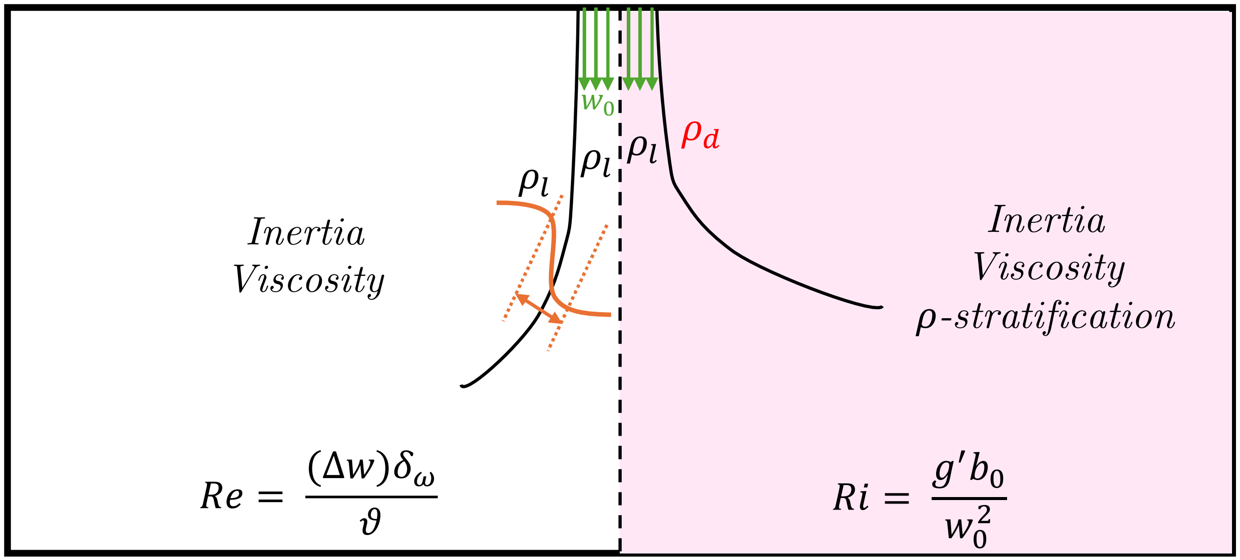


Buoyant gravity currents



Viscosity-stratified jets

Jet instability

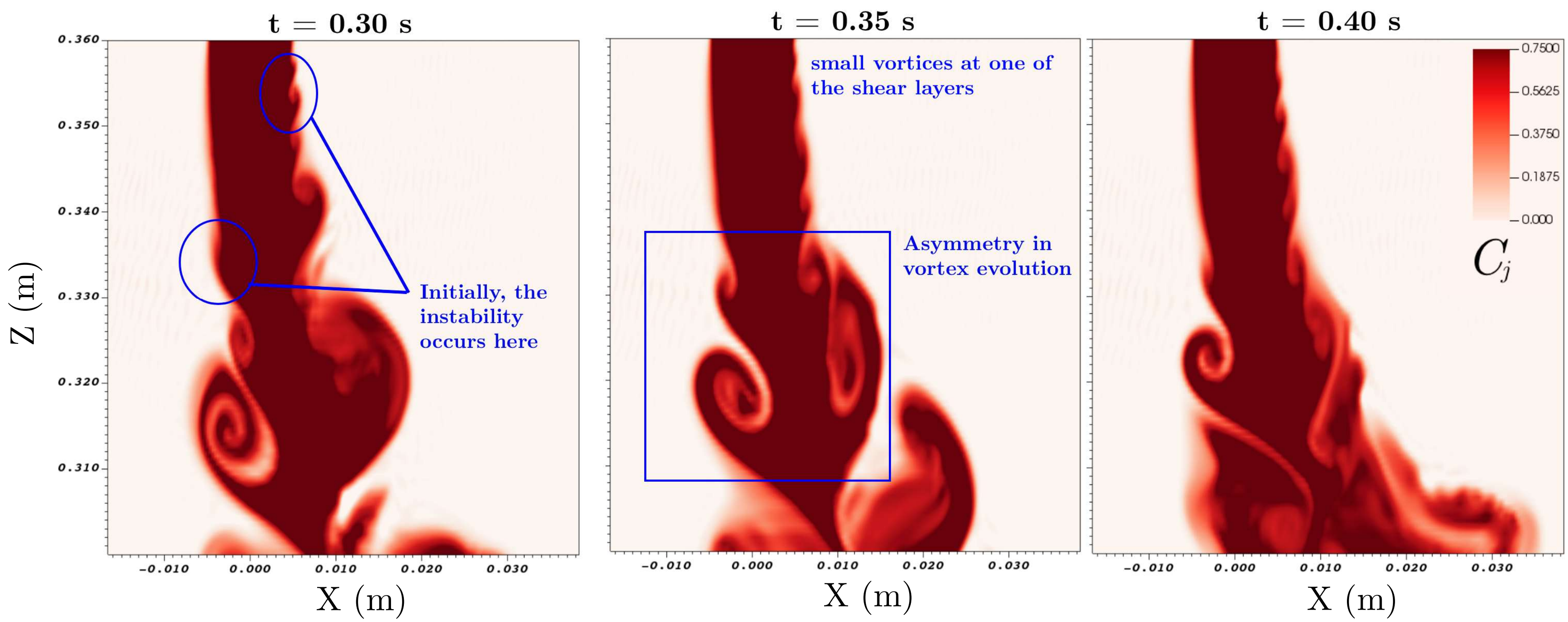


Critical value: ~ 50

Critical value: 0.25

Different mode/route of instabilities possible?

Jet instability



Asymmetry in instabilities → bypass transition??

Publications

1. T Agrawal, NK Jha, VK Chalamalla, Numerical investigation of air curtain flows in the doorway of a building using RANS and LES. **Computers & Fluids** (2023).
2. T Agrawal, S Agarwal, VK Chalamalla, NK Jha, Performance and flow dynamics of heavy air curtains using experiments and numerical simulations. **Environmental Fluid Mechanics** (2024).
3. T Agrawal, NK Jha, VK Chalamalla, Implications of cross-stream buoyancy on the dynamics of turbulent impinging line fountains. (In Revision, JFM).
4. T Agrawal, VK Chalamalla, NK Jha, Infiltration and transport dynamics in air curtains. (Under review in JFM).

Peer-reviewed presentations in Conference: 4 (1 international + 3 national)
Poster presentation at FDSE Summer School, University of Cambridge
National poster presentation at PMRF symposium

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References

1. Hayes, F. C., and W. F. Stoecker. “Heat Transfer Characteristics of the Air Curtain.” *ASHRAE Transaction* 75, no. 2 (1969): 153–67.

2. Howell, Ronald H., and Masaru Shibata. “Optimum Heat Transfer Through Turbulent Recirculated Plane Air Curtains.” *ASHRAE Transaction* 2567, no. 122 (1980).

3. Guyonnaud, L., C. Solliec, M. Dufresne De Virel, and C. Rey. “Design of Air Curtains Used for Area Confinement in Tunnels.” *Experiments in Fluids* 28, no. 4 (April 3, 2000): 377–84. https://doi.org/10.1007/s003480050397.

4. Foster, A.M., M.J. Swain, R. Barrett, P. D'Agaro, L.P. Ketteringham, and S.J. James. “Three-Dimensional Effects of an Air Curtain Used to Restrict Cold Room Infiltration.” *Applied Mathematical Modelling* 31, no. 6 (June 2007): 1109–23. https://doi.org/10.1016/j.apm.2006.04.005.

5. Frank, D., and P. F. Linden. “The Effectiveness of an Air Curtain in the Doorway of a Ventilated Building.” *Journal of Fluid Mechanics* 756 (October 10, 2014): 130–64. https://doi.org/10.1017/jfm.2014.433.

6. Frank, D., and P.F. Linden. “The Effects of an Opposing Buoyancy Force on the Performance of an Air Curtain in the Doorway of a Building.” *Energy and Buildings* 96 (June 2015): 20–29. https://doi.org/10.1016/j.enbuild.2015.02.046.

7. Jha, Narsing K., D. Frank, L. Darracq, and P.F. Linden. “Contaminant Transport by Human Passage through an Air Curtain Separating Two Sections of a Corridor: Part II – Two Zones at Different Temperatures.” *Energy and Buildings* 236 (April 2021): 110728. https://doi.org/10.1016/j.enbuild.2021.110728.

8. Gonçalves, J.C., J.J. Costa, A.R. Figueiredo, and A.M.G. Lopes. “CFD Modelling of Aerodynamic Sealing by Vertical and Horizontal Air Curtains.” *Energy and Buildings* 52 (September 2012): 153–60. https://doi.org/10.1016/j.enbuild.2012.06.007.

9. Khayrullina, A., T. Van Hooff, B. Blocken, and G. J. F. Van Heijst. “PIV Measurements of Isothermal Plane Turbulent Impinging Jets at Moderate Reynolds Numbers.” *Experiments in Fluids* 58, no. 4 (April 2017): 31. https://doi.org/10.1007/s00348-017-2315-0.

10. Khayrullina, Adelya, Twan Van Hooff, Bert Blocken, and GertJan Van Heijst. “Validation of Steady RANS Modelling of Isothermal Plane Turbulent Impinging Jets at Moderate Reynolds Numbers.” *European Journal of Mechanics - B/Fluids* 75 (May 2019): 228–43. https://doi.org/10.1016/j.euromechflu.2018.10.003.

11. Alanis Ruiz, Claudio, Twan Van Hooff, Bert Blocken, and GertJan Van Heijst. “Air Curtain Performance: Introducing the Adapted Separation Efficiency.” *Building and Environment* 188 (January 2021): 107468. https://doi.org/10.1016/j.buildenv.2020.107468.

12. Hunt, G.R., and H.C. Burridge. “Fountains in Industry and Nature.” *Annual Review of Fluid Mechanics* 47, no. 1 (January 3, 2015): 195–220. https://doi.org/10.1146/annurev-fluid-010313-141311.

13. Morton, B. R., Geoffrey Taylor, and J. S. Turner. “Turbulent Gravitational Convection from Maintained and Instantaneous Sources.” *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 234, no. 1196 (1956): 1–23.

14. Ramaprian, B. R., and M. S. Chandrasekhara. “Measurements in Vertical Plane Turbulent Plumes.” *Journal of Fluids Engineering* 111, no. 1 (March 1, 1989): 69–77. https://doi.org/10.1115/1.3243602.

15. Paillat, S., and E. Kaminski. “Second-Order Model of Entrainment in Planar Turbulent Jets at Low Reynolds Number.” *Physics of Fluids* 26, no. 4 (April 1, 2014): 045110. https://doi.org/10.1063/1.4871521.

16. Haller, George. *Transport Barriers and Coherent Structures in Flow Data: Advective, Diffusive, Stochastic and Active Methods.* 1st ed. Cambridge University Press, 2023. https://doi.org/10.1017/9781009225199.

I thank you all for your time and attention,
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