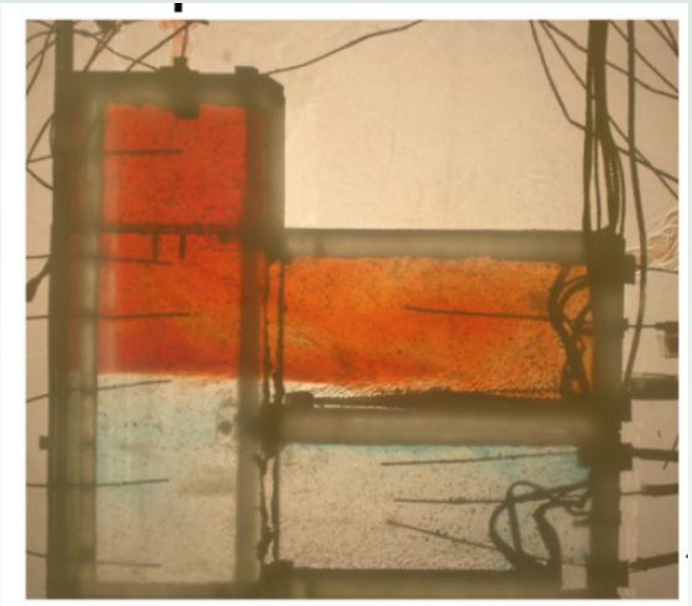
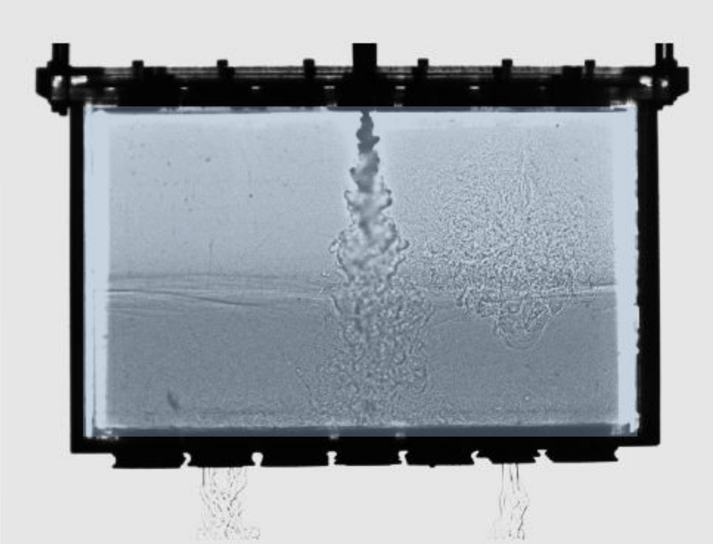
Modelling natural ventilation:

Small-scale experiments in water

Andy Acred





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Overview

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Introduction to water bath modelling

- Why experiment?
- Overview of techniques: heat & salt

Capabilities: some case studies

- Combined wind and buoyancy
- Discharge coefficient and exchange flows

Why experiment?

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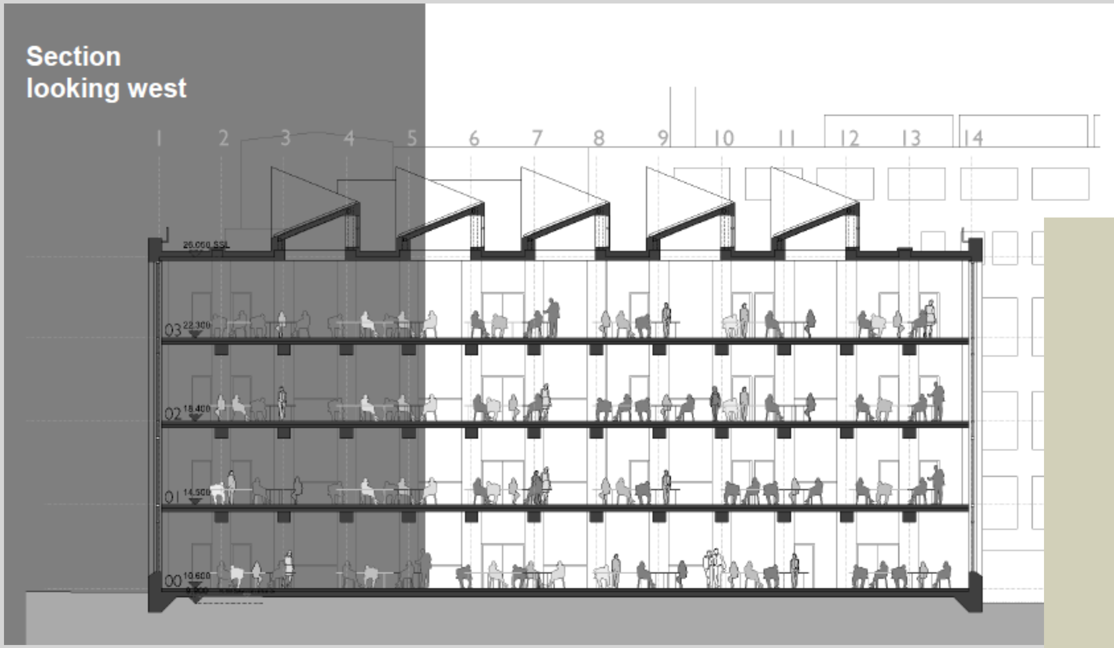
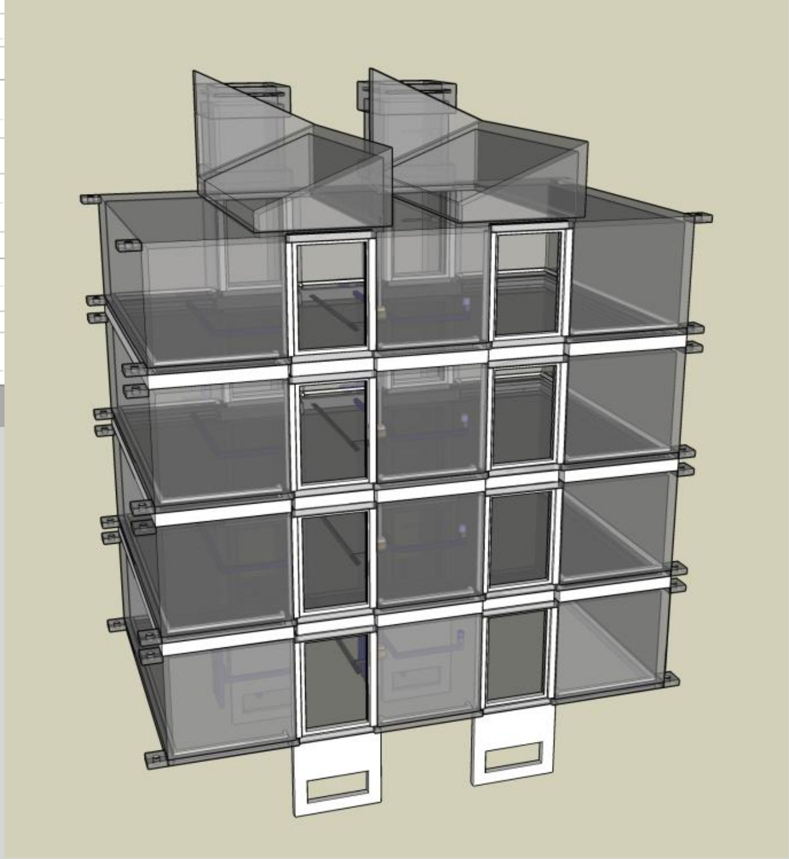
- Real-time, 3-D fluid flows
- Flow visualisation
- Capture specific flow phenomena
- Validate theory
- Push forward intuitive understanding

The experimental method

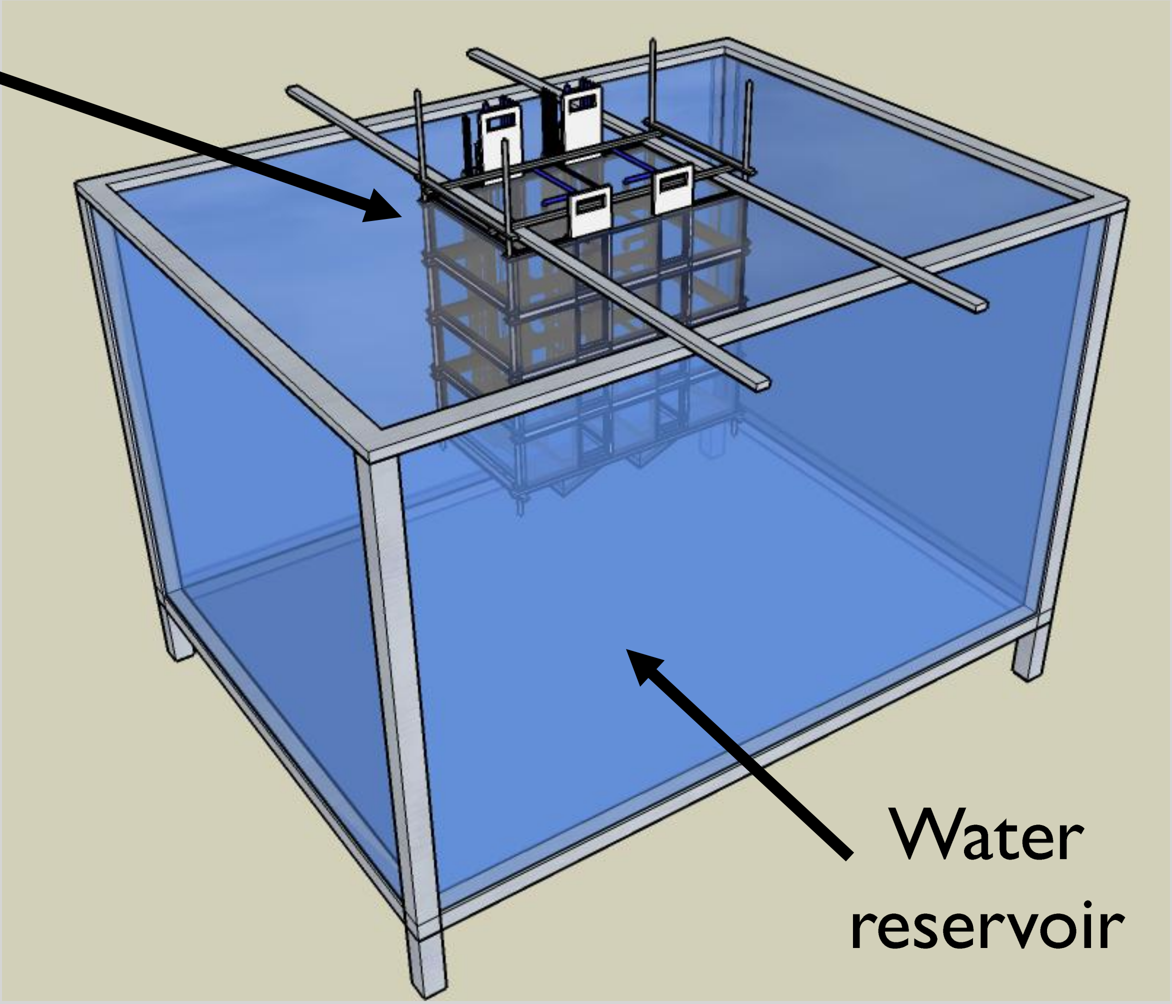


Full-scale design

1:20 – 1:50
scale model



The experimental method



Buoyancy sources

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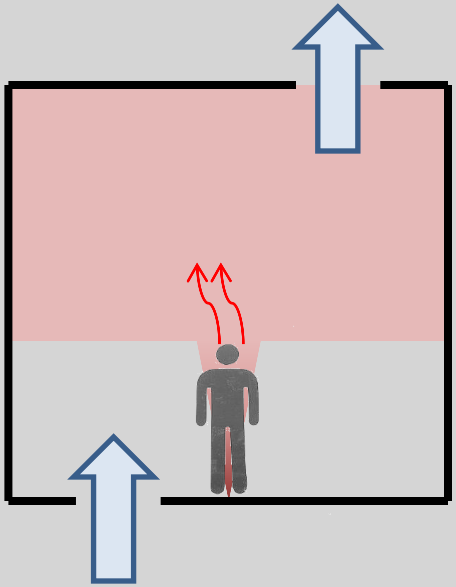
FULL SCALE

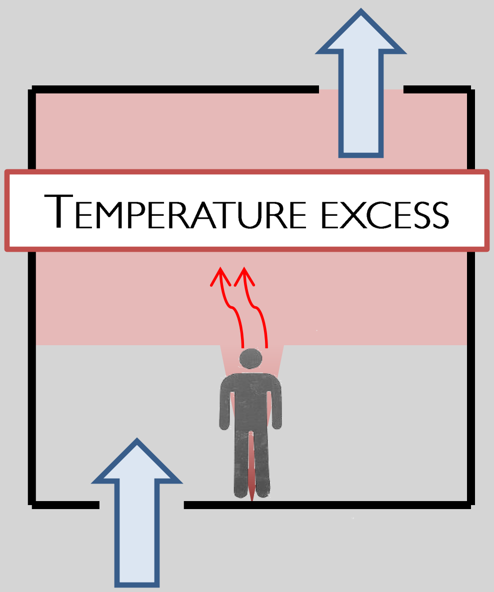
Heat in air



Buoyancy sources

FULL SCALE

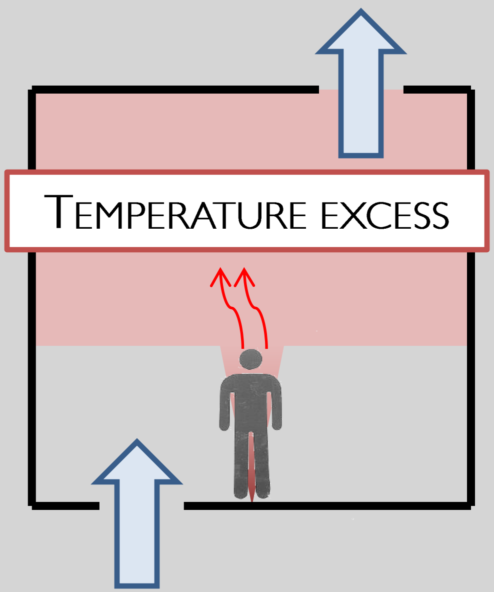
Heat in air



Buoyancy sources

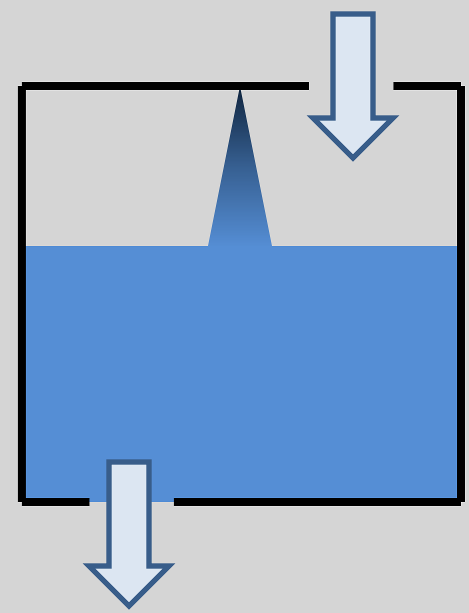
FULL SCALE

Heat in air



MODEL SCALE

Saline in water



Buoyancy sources

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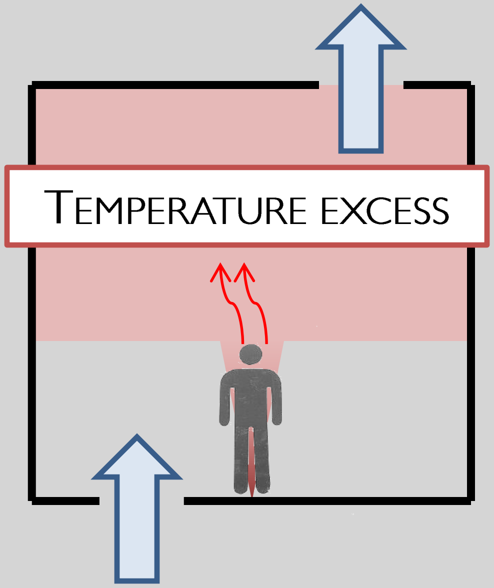
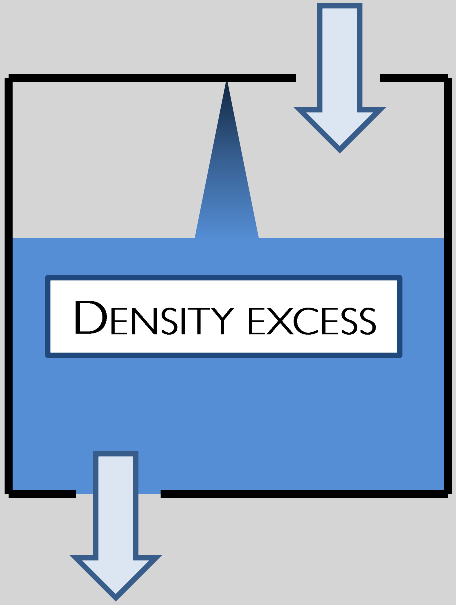
FULL SCALE

MODEL SCALE

Heat in air

Saline in water





Buoyancy sources

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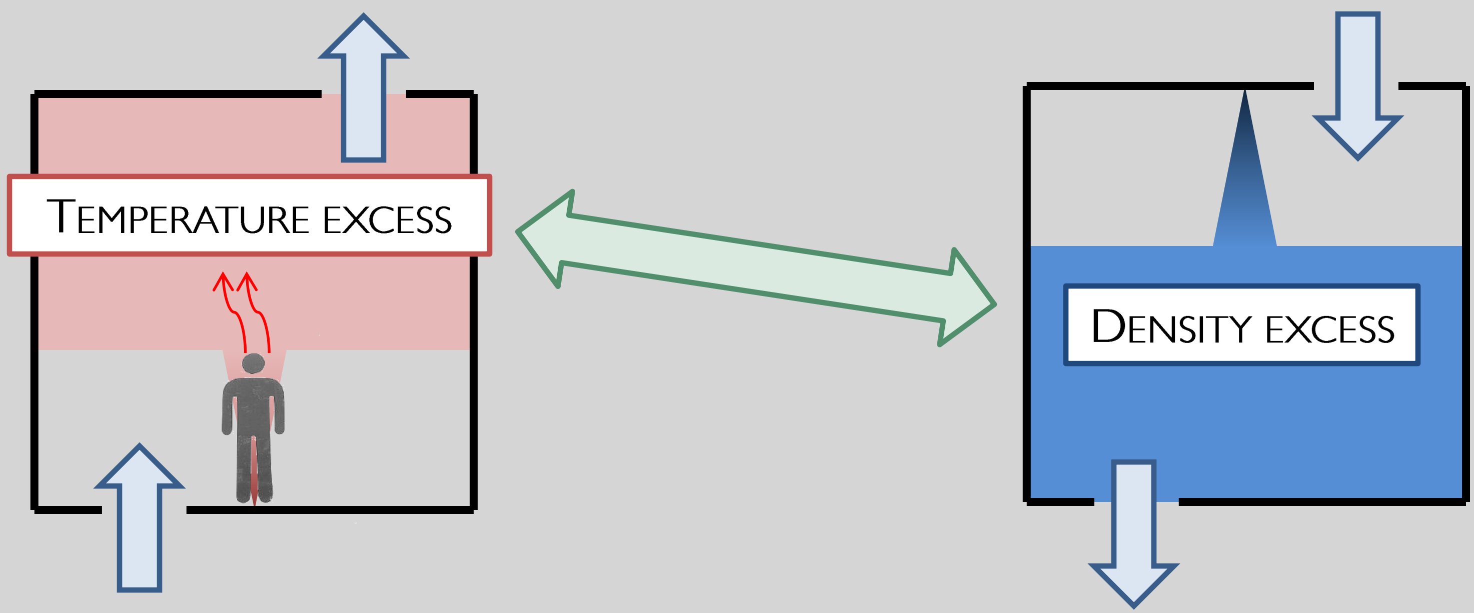
FULL SCALE | EQUIVALENT FLUID DYNAMICS | MODEL SCALE

Heat in air ⟷ Saline in water



Buoyancy sources

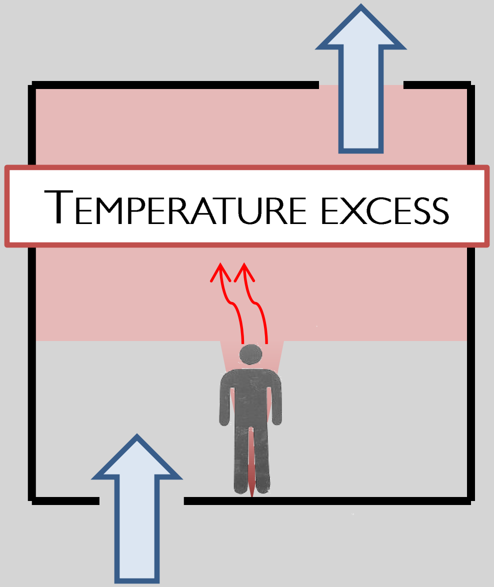
FULL SCALE

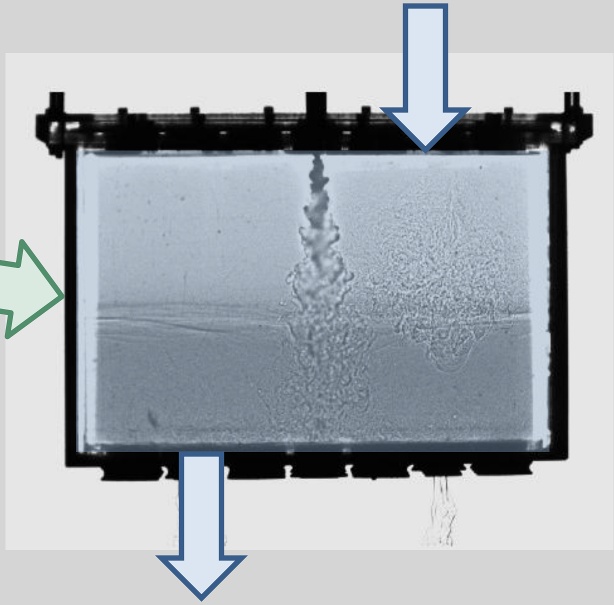
EQUIVALENT FLUID DYNAMICS

MODEL SCALE

Heat in air

Saline in water





Dye attenuation technique

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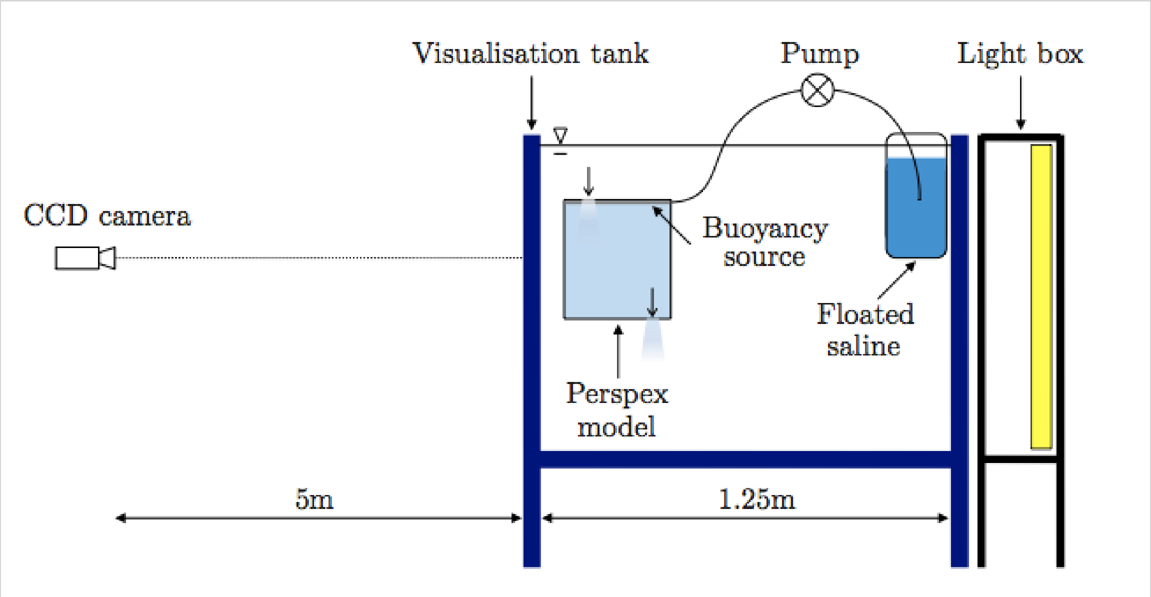
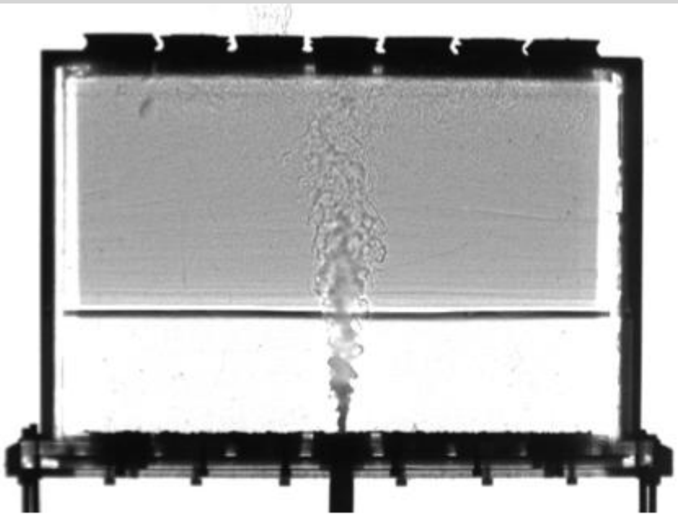
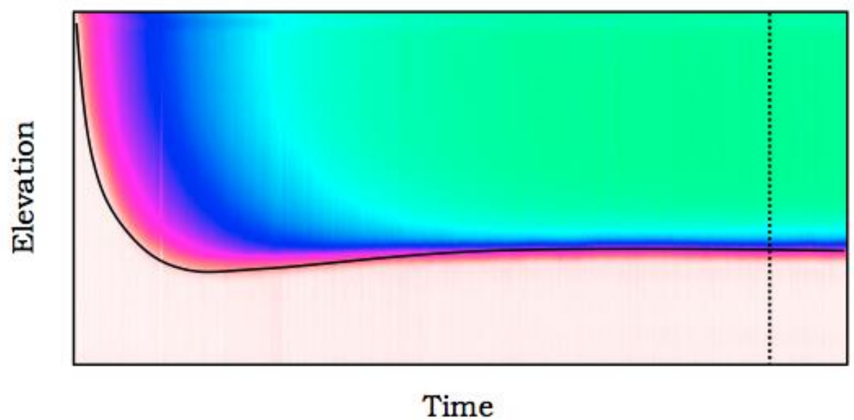


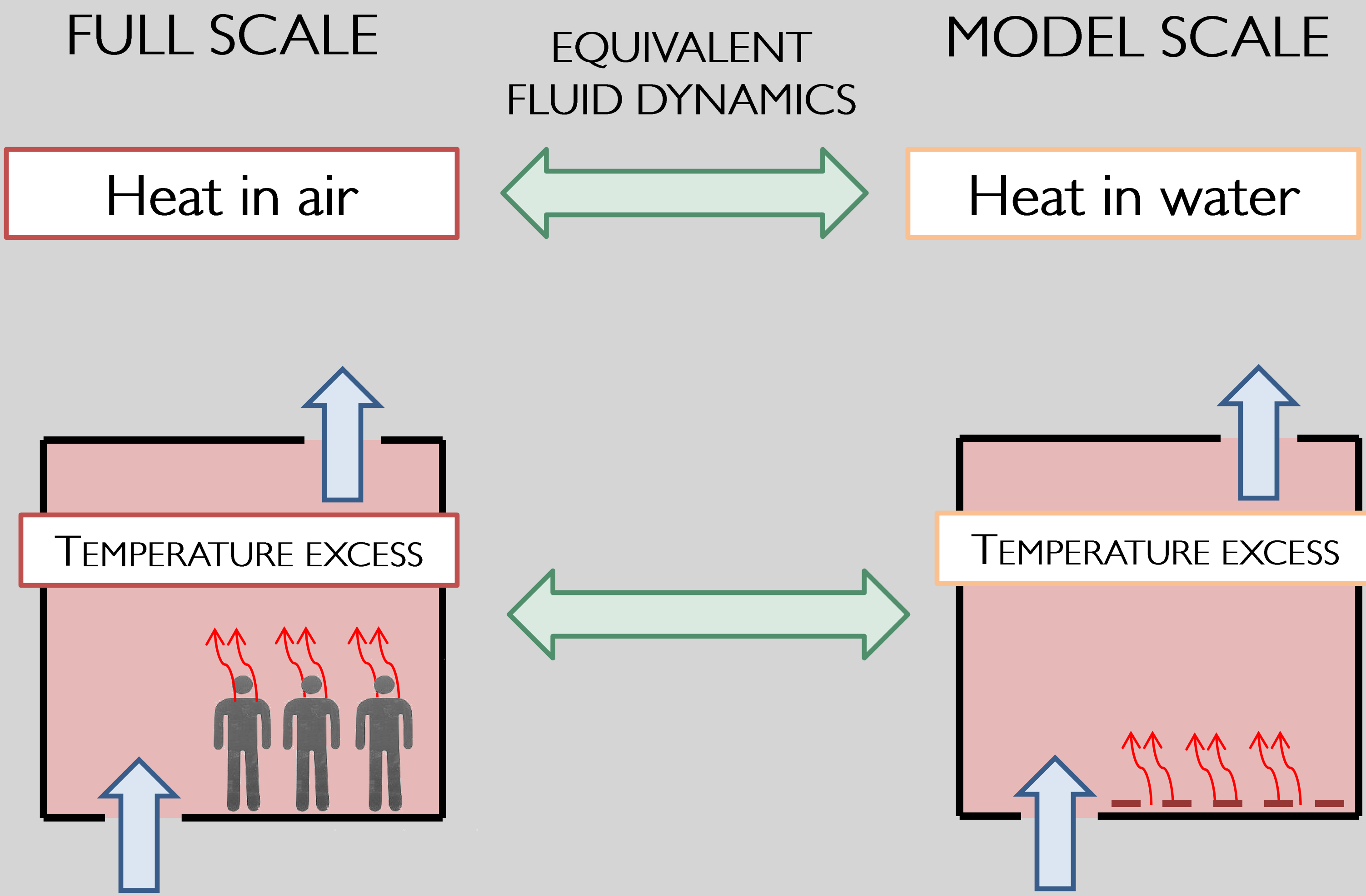
Light transmittance
↓
Salinity
↓
Temperature at full scale





LARICE (2009)

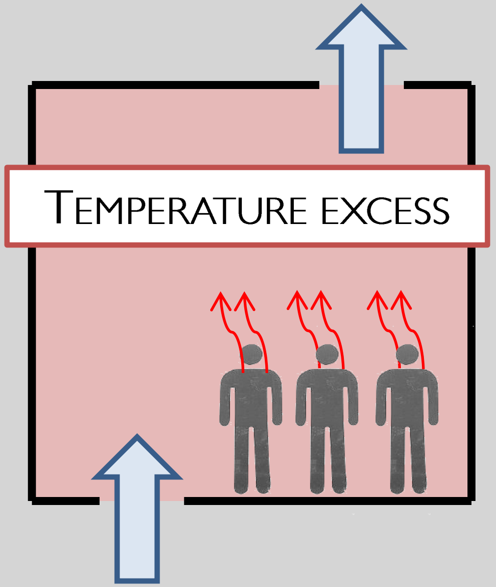
Buoyancy sources

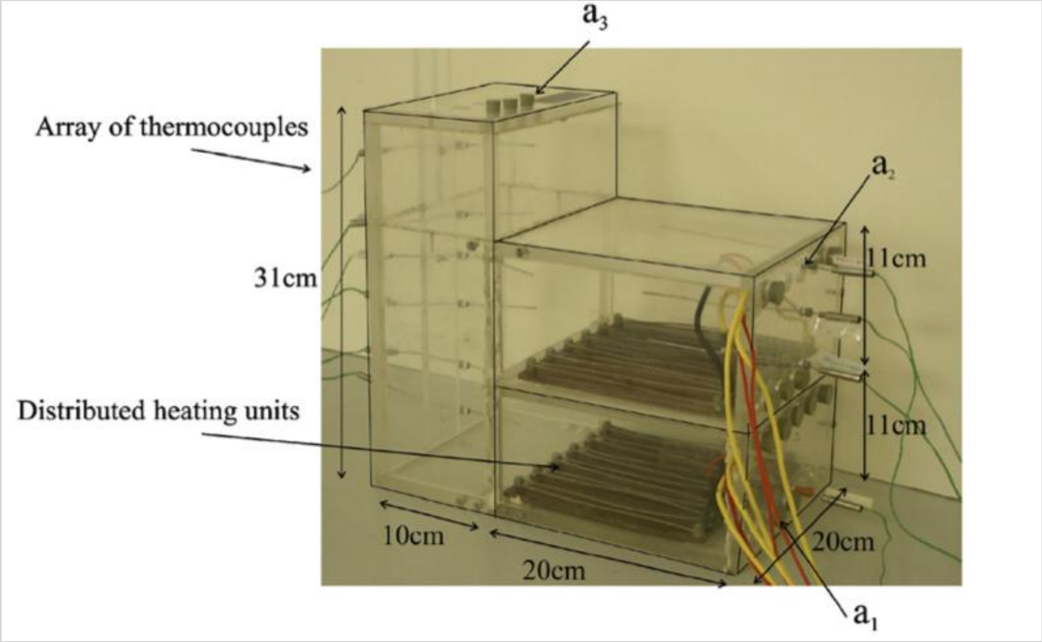


Buoyancy sources

FULL SCALE | EQUIVALENT FLUID DYNAMICS | MODEL SCALE

Heat in air ⟷ Heat in water





LIVERMORE & WOODS (2007)

Buoyancy sources

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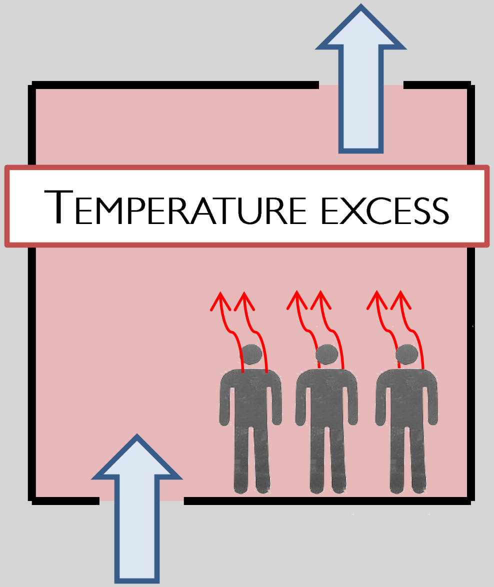
FULL SCALE

EQUIVALENT FLUID DYNAMICS

MODEL SCALE

Heat in air

Heat in water



PARTRIDGE & LINDEN (2013)

Dynamic similarity

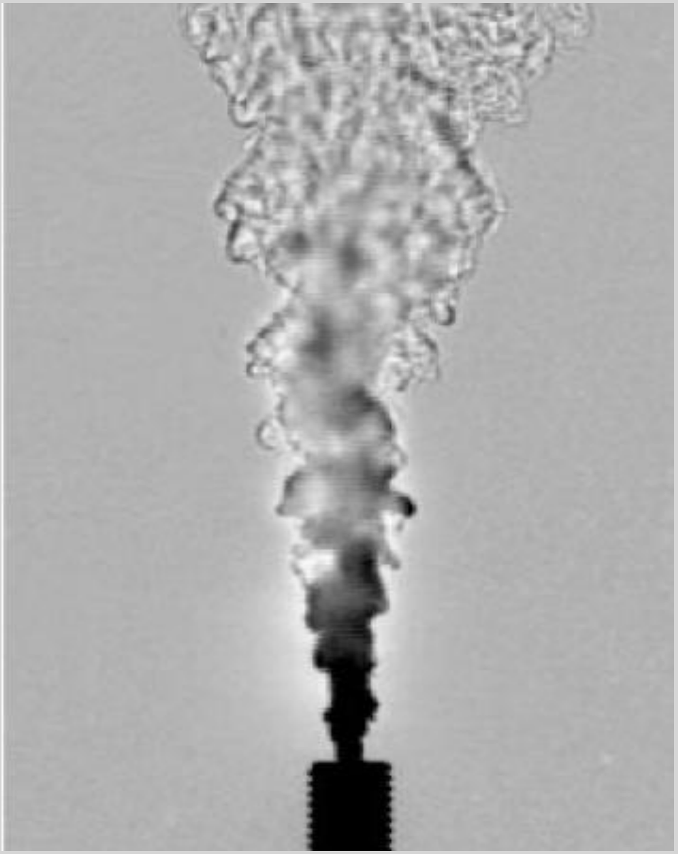
$$\mathrm{Re} = \frac{\text{Inertia}}{\text{Viscosity}} \gtrsim 10^3$$

$$\mathrm{Pe} = \frac{\text{Advection}}{\text{Diffusion}} \gtrsim 10^3$$

$$\mathrm{Ra} = \frac{\text{Convection}}{\text{Conduction}} \gtrsim 10^8$$

$$\mathrm{Fr} = \frac{\text{Inertia}}{\text{Buoyancy}}$$

Turbulent flows in which heat (buoyancy) transport occurs by advection



HUNT & LINDEN (2001)

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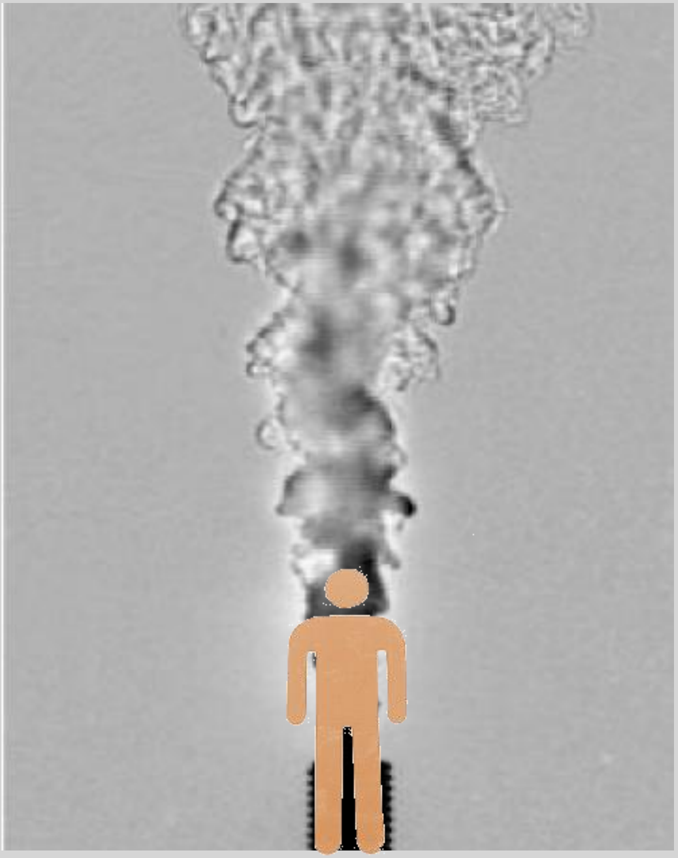

HUNT & LINDEN (2001)

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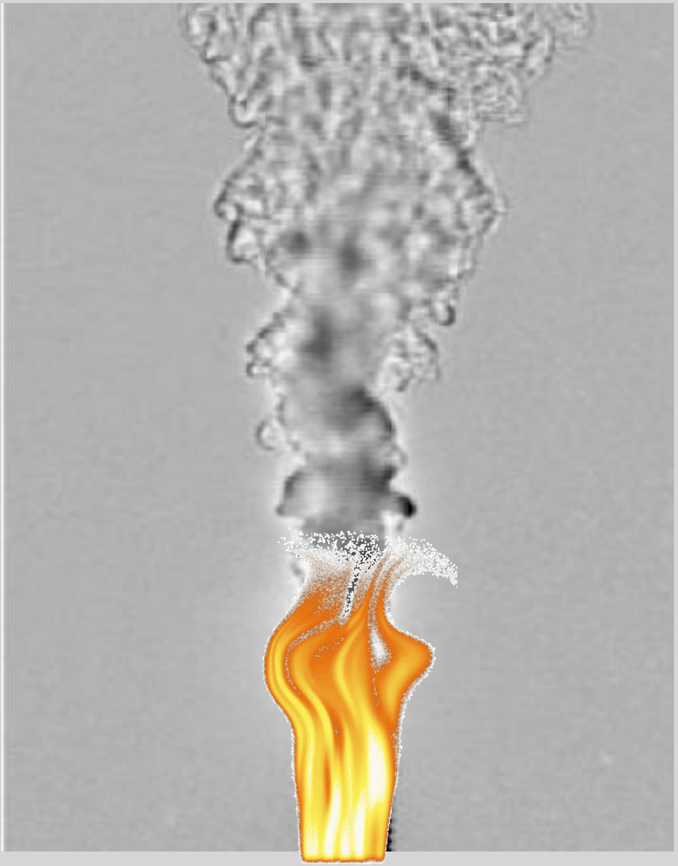


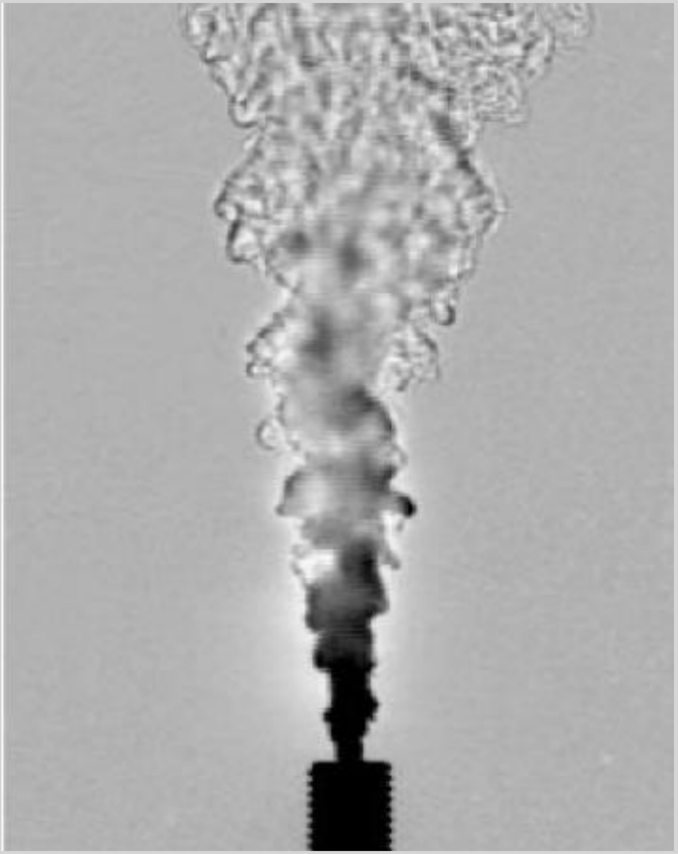
HUNT & LINDEN (2001)

Dynamic similarity

Heat in water

Partridge & Linden (2013)

Salt in water



Hunt & Linden (2001)

Comparison of methods

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Heat in water

- Wires or hot plates (no volume flux)
- Smaller density differences
- Measurement by thermocouples or thermistors

Salt in water

- Direct injection of saline
- Adiabatic walls
- Large density difference ($\Delta\rho/\rho \sim 0.2$) possible
- Measurement by salinity probes or dye attenuation technique

- Dye & shadowgraph visualisation

Modelling heat sources

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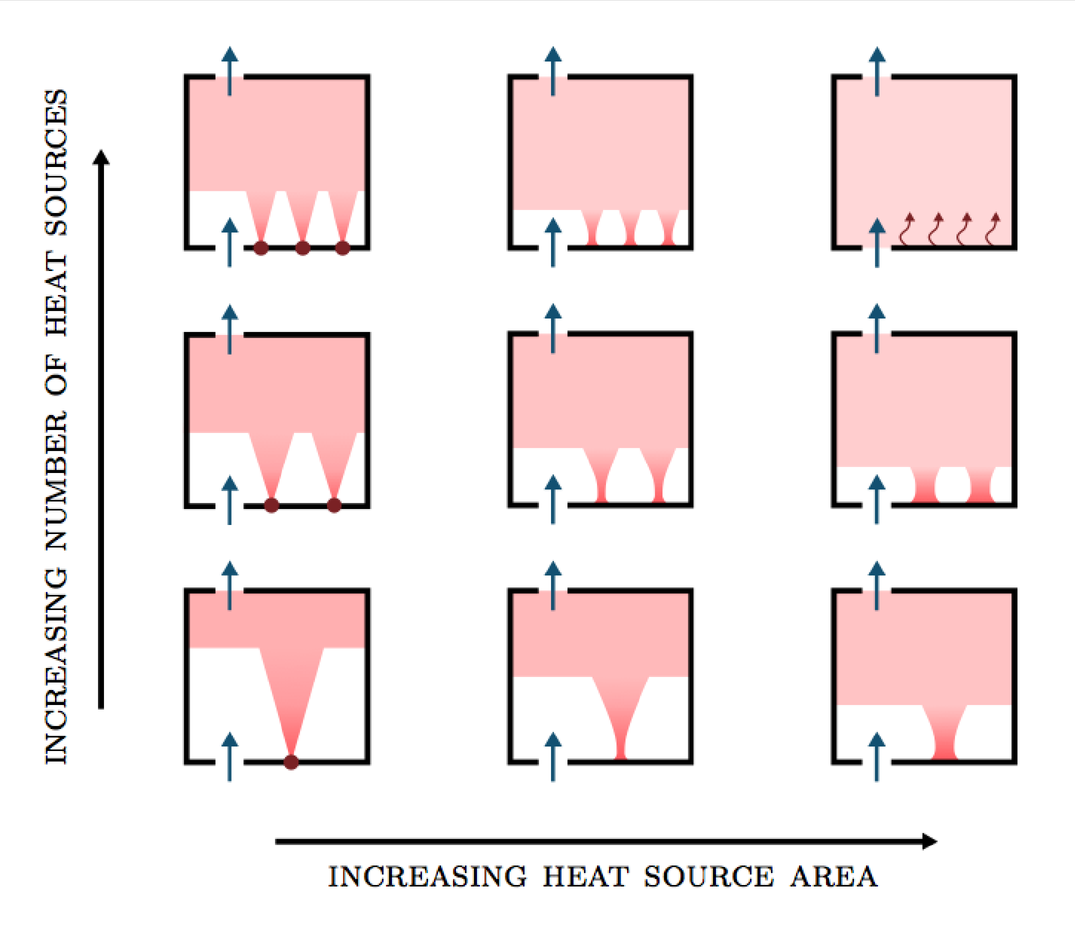

'Underfloor heating'

GLADSTONE & WOODS (2001)

(or 'Chilled ceiling')

'Single person'

LINDEN ET AL (1990)

Modelling heat sources

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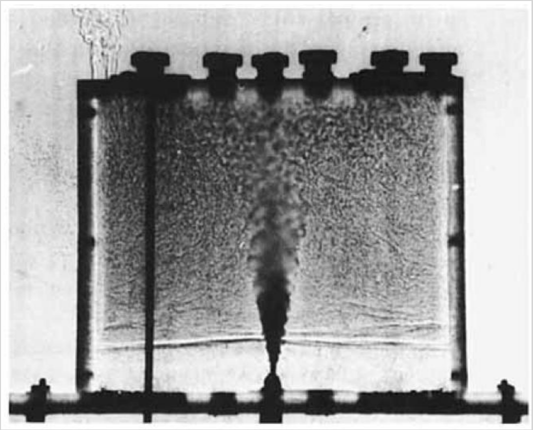
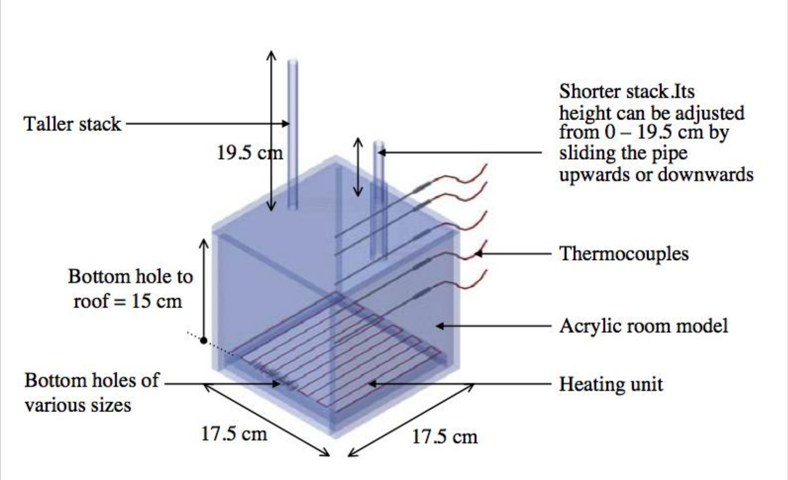
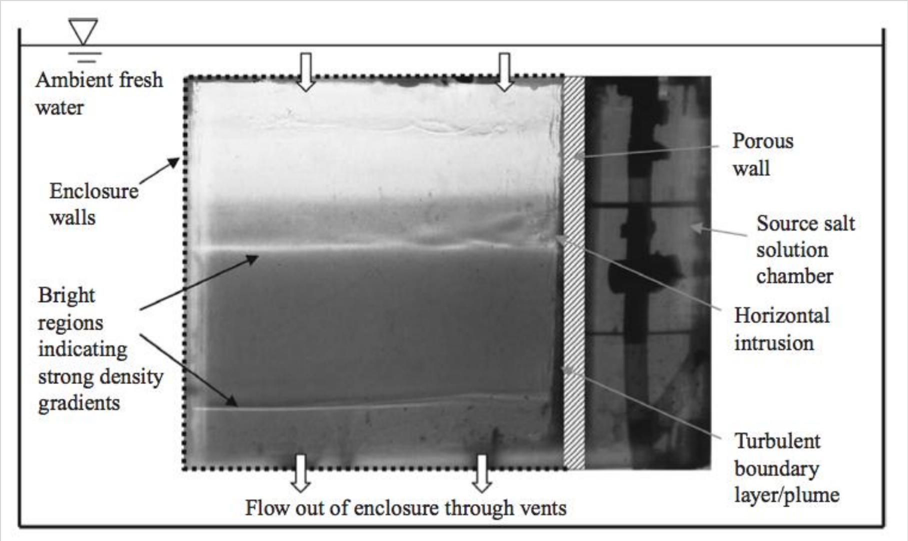


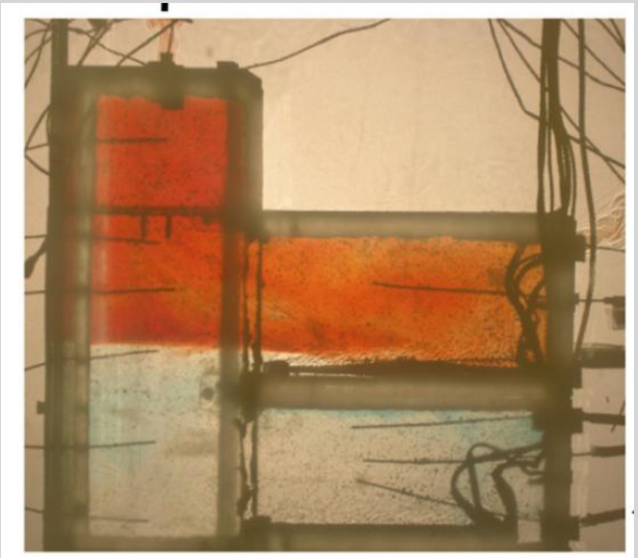
LINDEN ET AL (1990)



CHENVIDYAKARN & WOODS (2005)

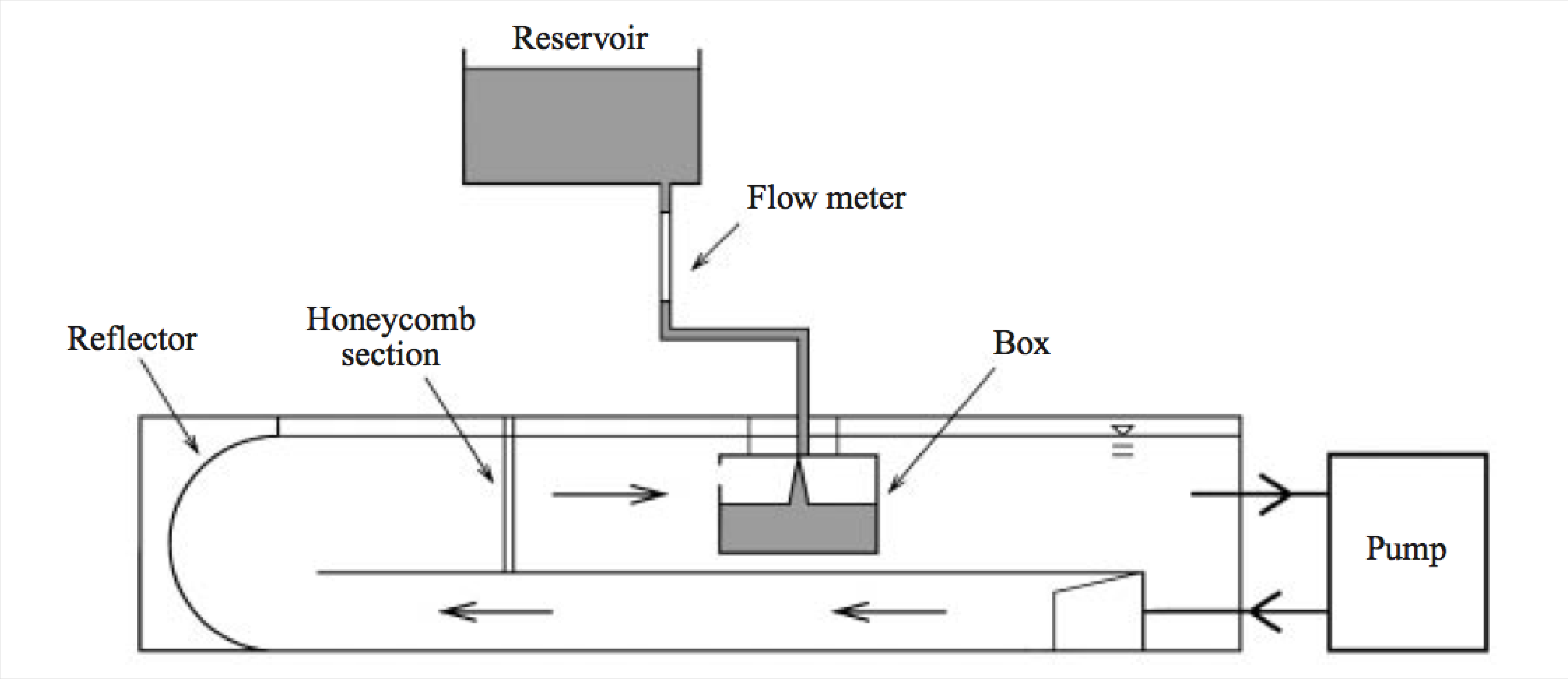


COOPER & HUNT (2010)



LIVERMORE & WOODS (2007)

Salt in water with a recirculating flume



Hunt & Linden (2001)

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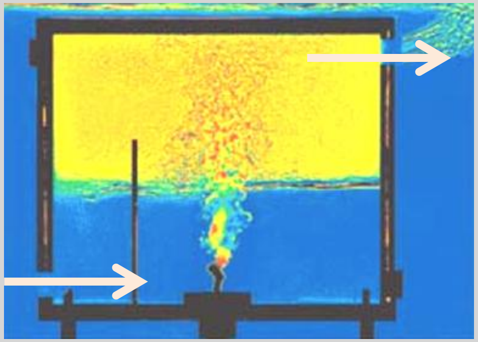
Multiple steady flow regimes

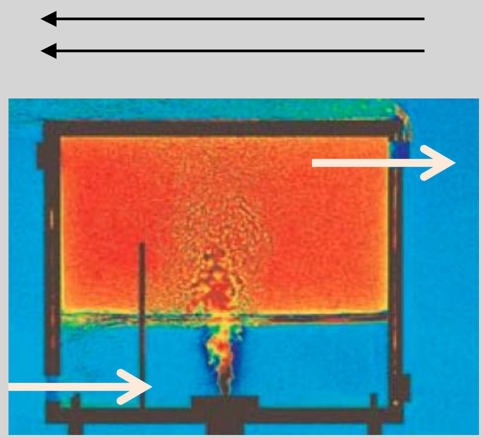
'No wind'



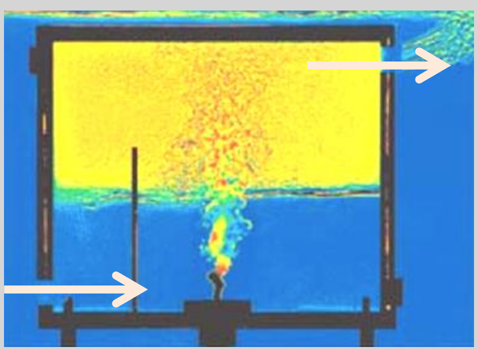
Combining wind & buoyancy

Multiple steady flow regimes

'Opposing wind'



'No wind'



Forward displacement flow

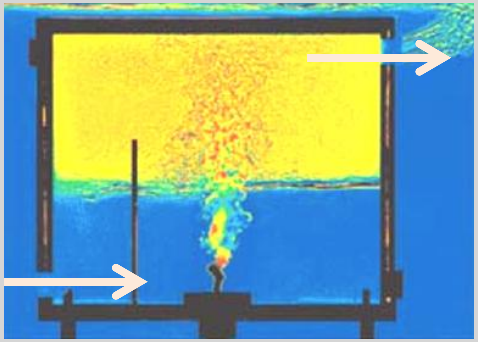
HUNT & LINDEN (2005)

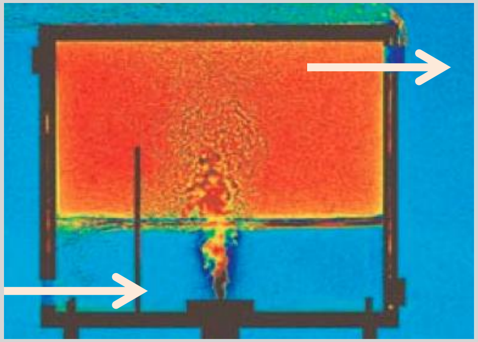
Combining wind & buoyancy

Multiple steady flow regimes

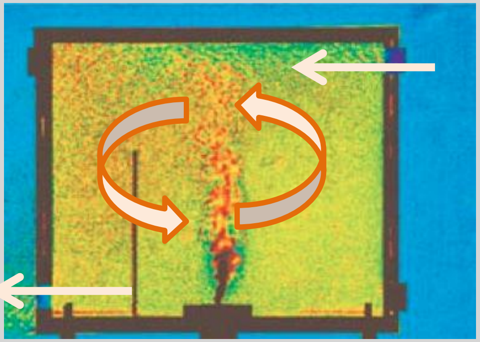
'Opposing wind'

'No wind'





Forward displacement flow



Reversed flow with mixing

HUNT & LINDEN (2005)

Combining wind & buoyancy

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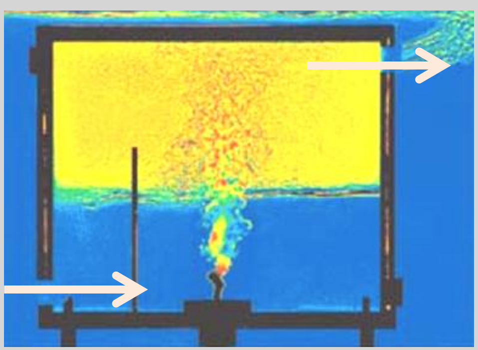
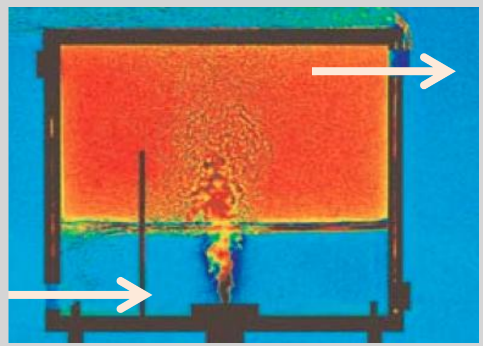
Multiple steady flow regimes

Time history dependent

'Opposing wind'

'No wind'





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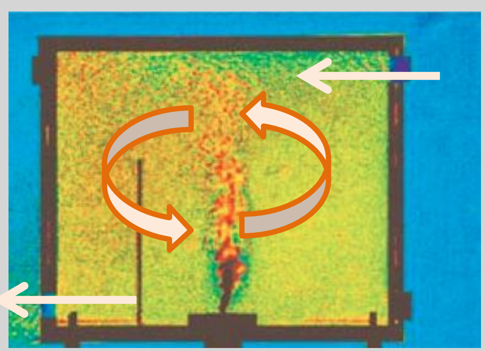
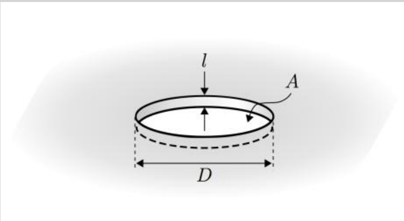


Reversed flow with mixing

HUNT & LINDEN (2005)

c_d and exchange flows



$$A_{effective} = c_d A_{geometric}$$

Viscous effects (friction)

Inertial effects (velocity profile)

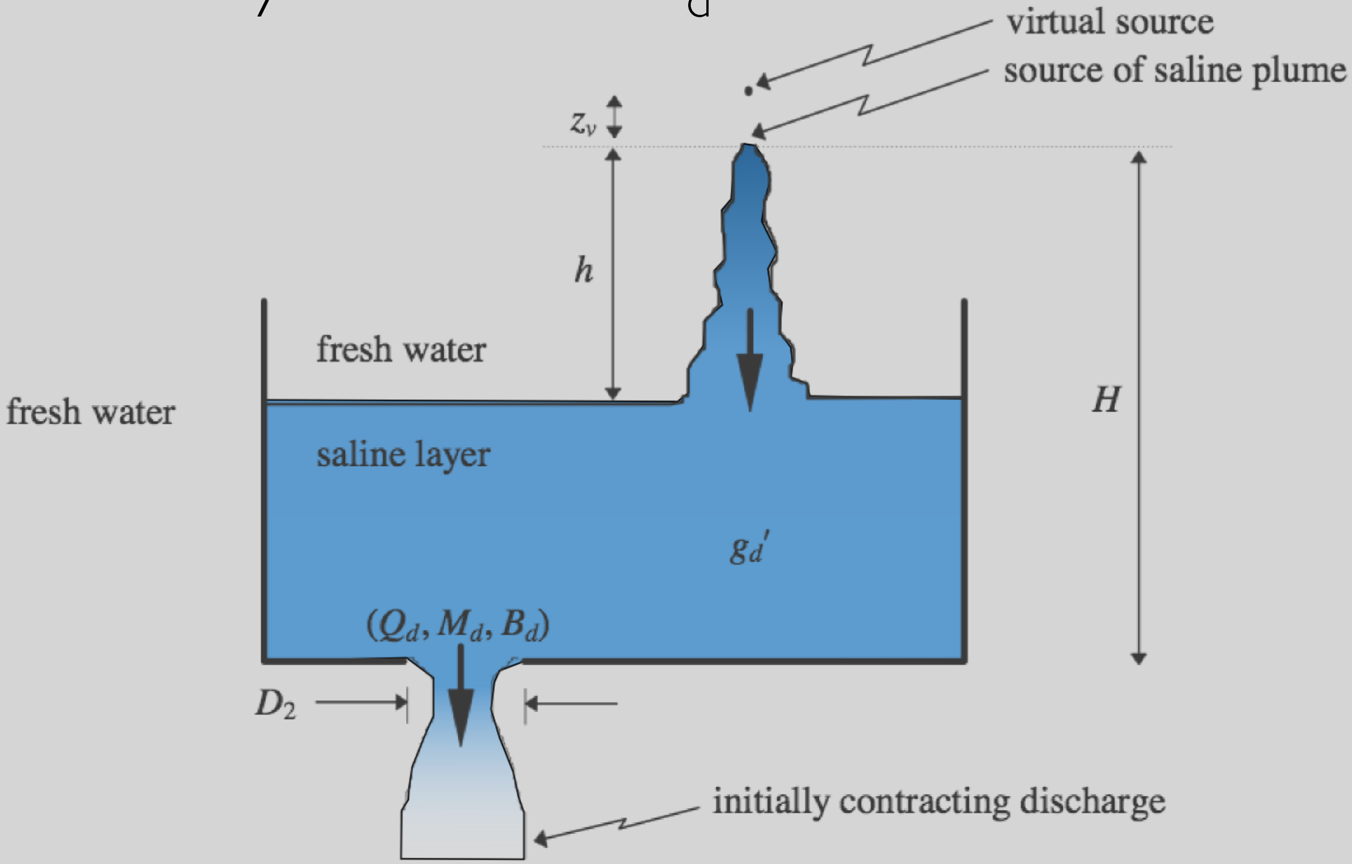
c_d

Buoyancy effects (density contrast)

Vent geometry

c_d and exchange flows

Holford & Hunt (2000 & 2001):
Experimental investigation of effect of density contrast on c_d



c_d and exchange flows

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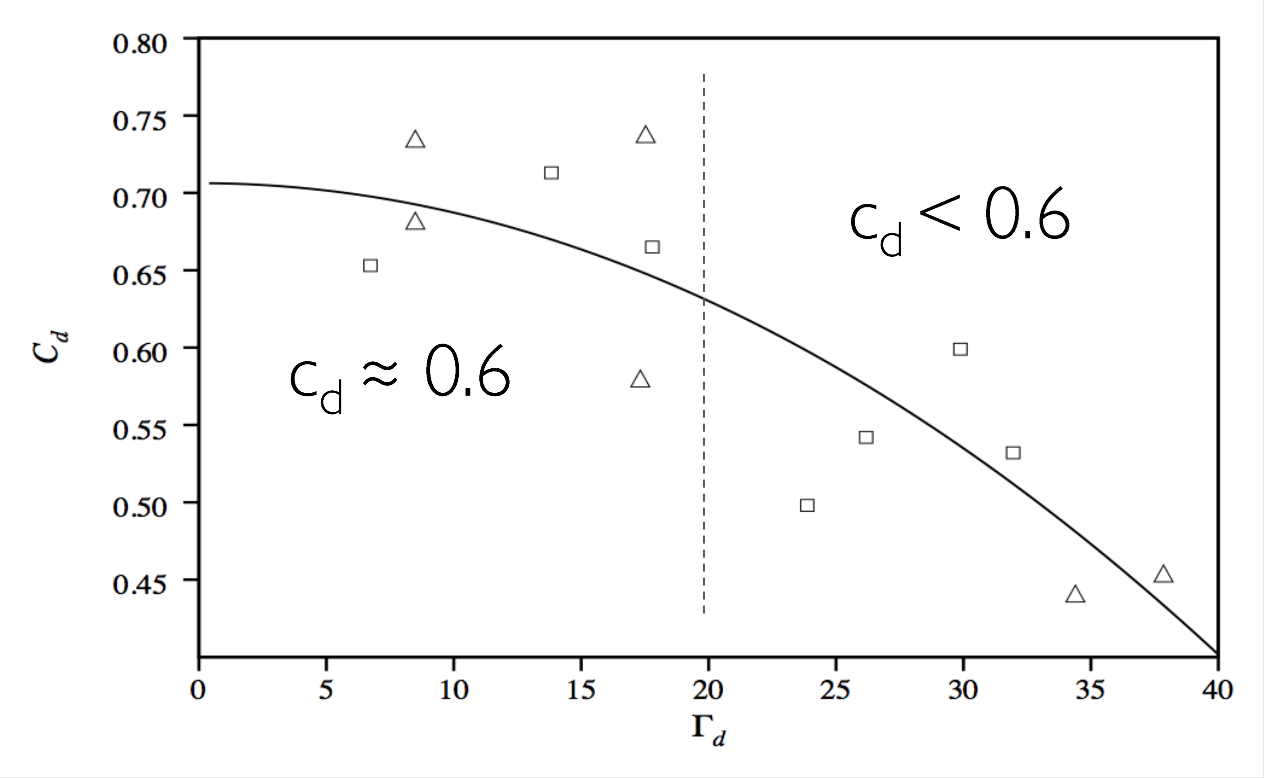
Increasing density contrast
AND/OR Increasing vent size
AND/OR Decreasing flow rate
→ Decreasing Fr



HUNT & HOLFORD (2000)

c_d and exchange flows

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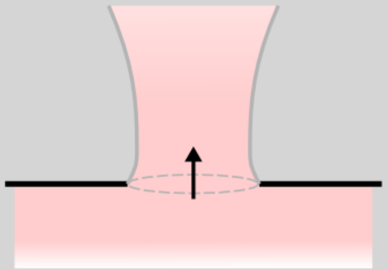
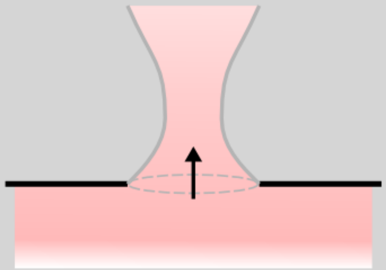


‘Normal’ unidirectional flow



Significant necking, decrease in c_d

HUNT & HOLFORD (2000 & 2001)

c_d and exchange flows

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AND/OR Increasing vent size
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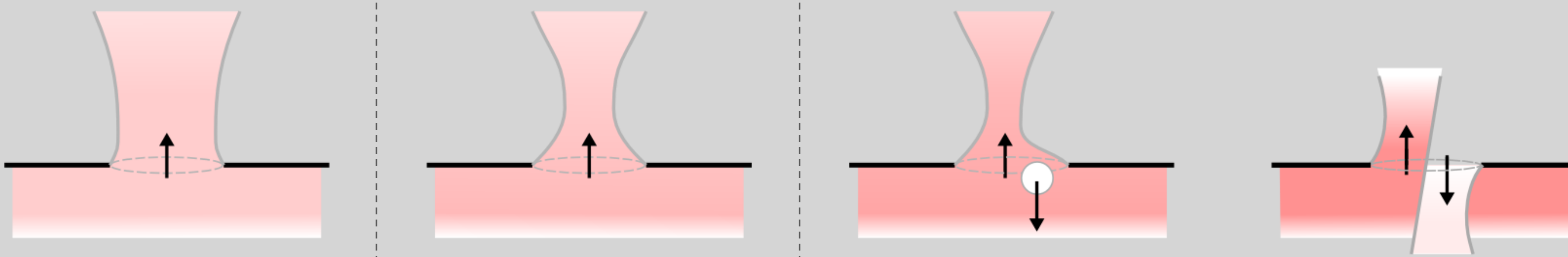

'Normal' unidirectional flow

Significant necking, decrease in c_d

Pulsing

Steady

Exchange flows

HUNT & HOLFORD (2000 & 2001)

HUNT & COFFEY (2010)

c_d and exchange flows

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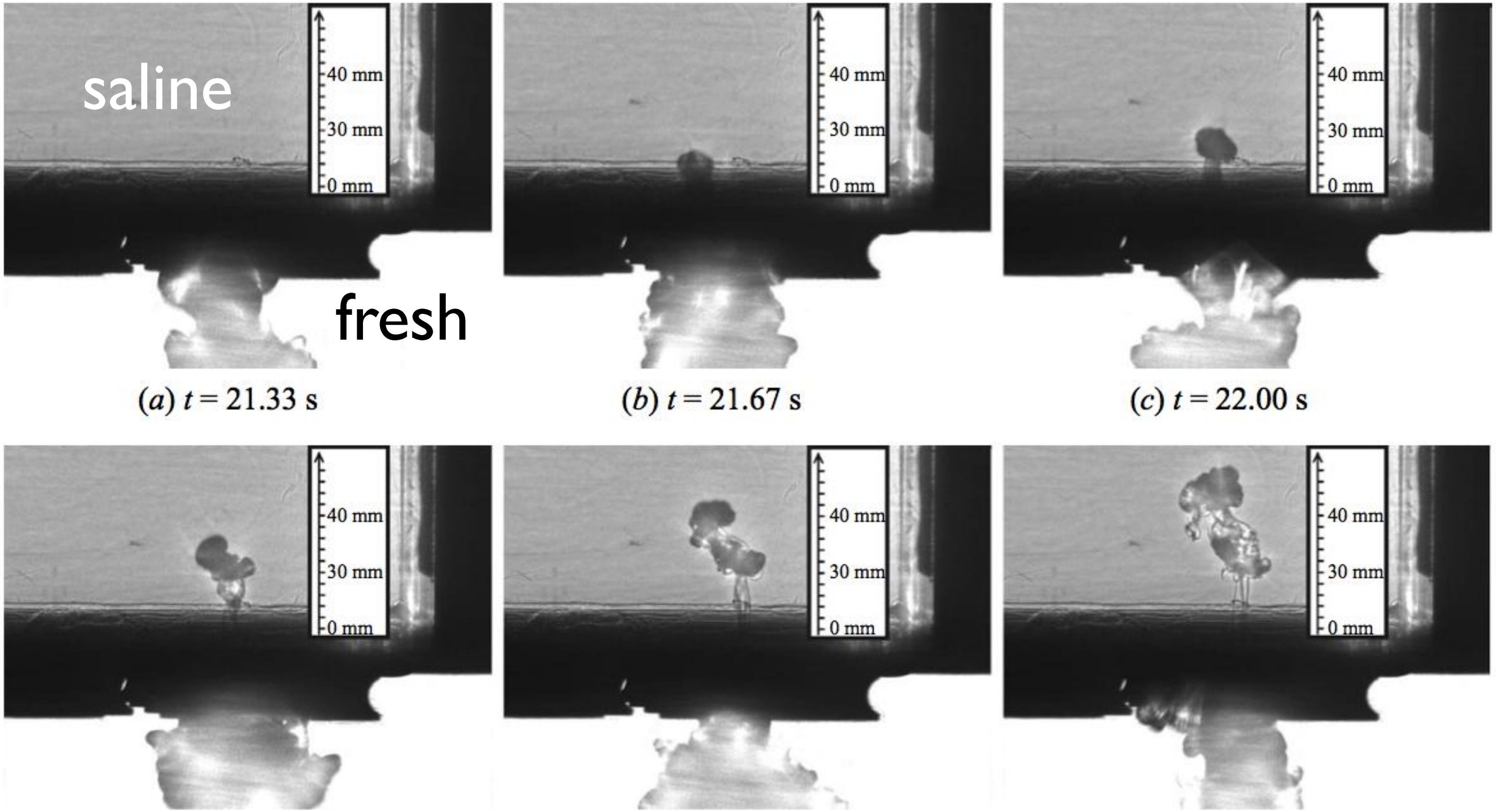
Pulsing exchange flow

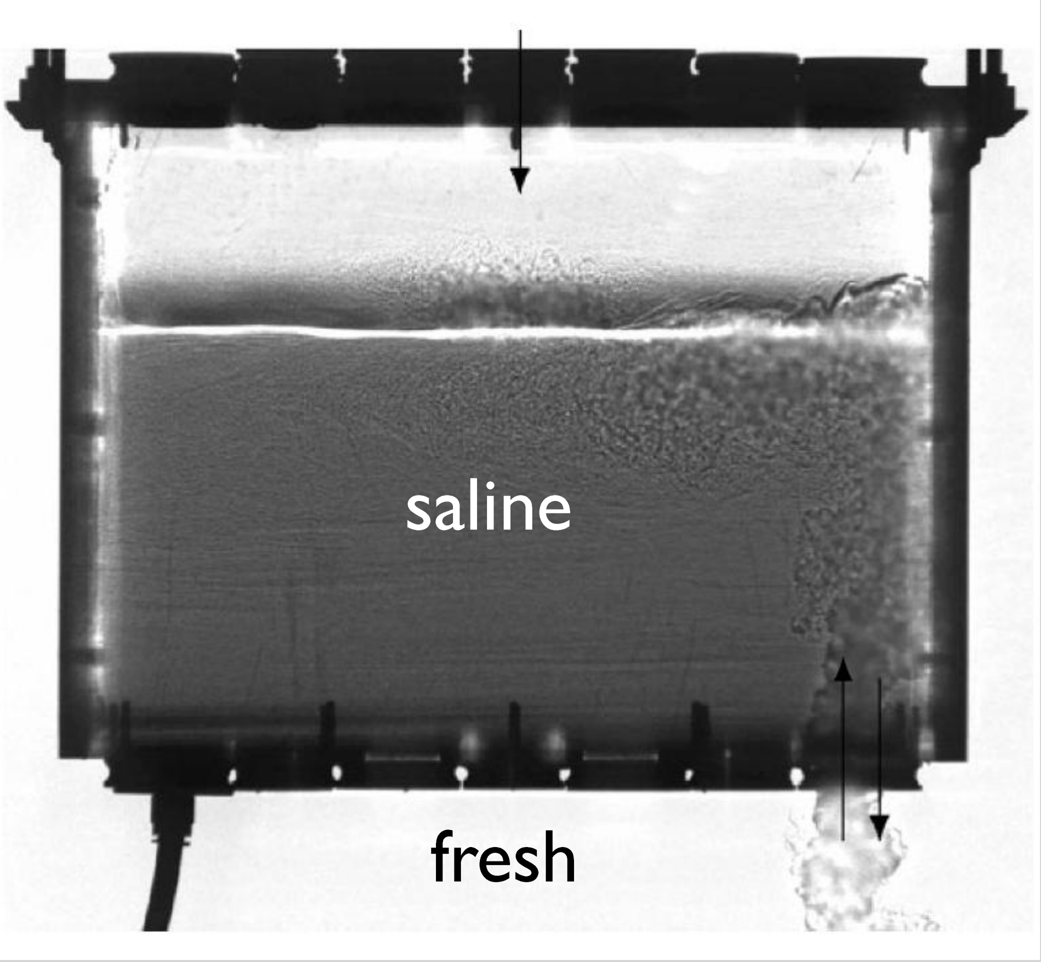


(*a*) $t = 21.33$ s (*b*) $t = 21.67$ s (*c*) $t = 22.00$ s
(*d*) $t = 22.33$ s (*e*) $t = 22.67$ s (*f*) $t = 23.00$ s

Hunt & Coffey (2010)

c_d and exchange flows

Steady exchange flow



Hunt & Coffey (2010)

c_d and exchange flows

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Increasing density contrast
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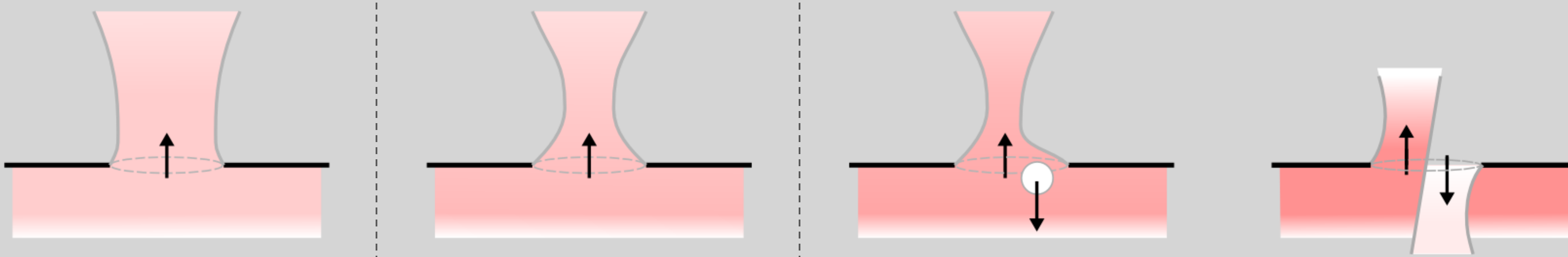


'Normal' unidirectional flow

Significant necking, decrease in c_d

Pulsing

Steady

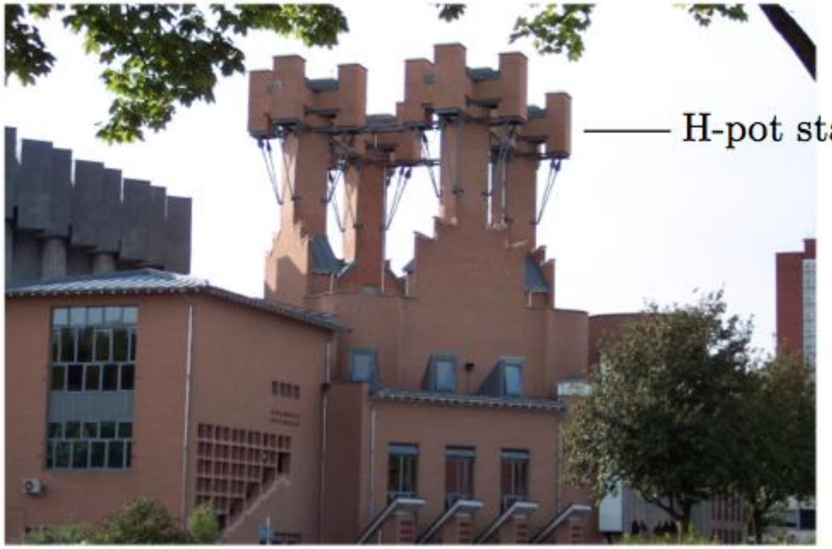
Exchange flows

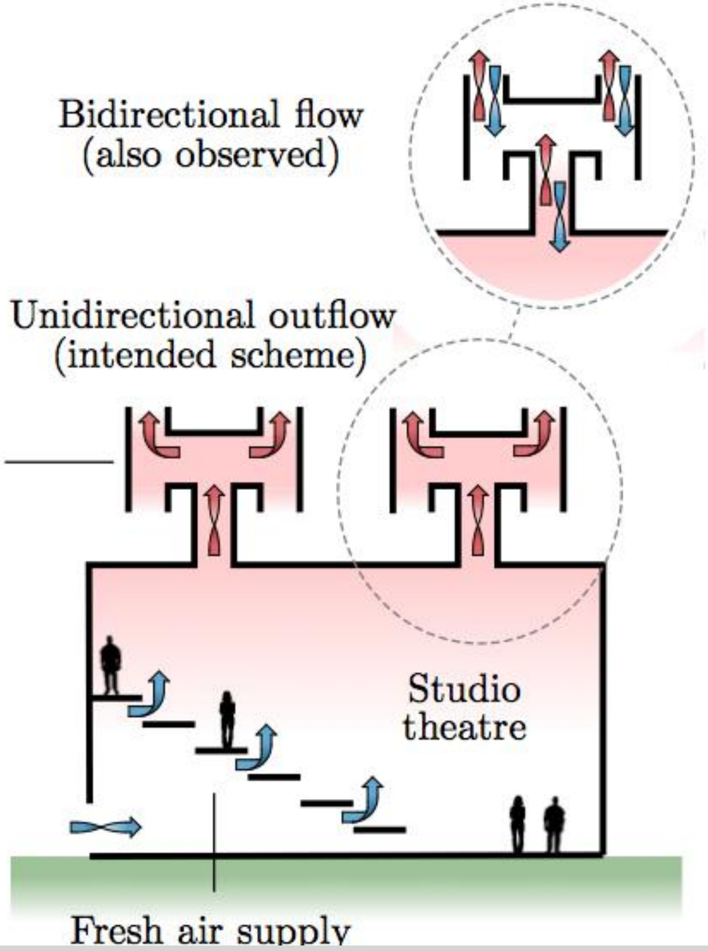
HUNT & HOLFORD (2000 & 2001)

HUNT & COFFEY (2010)

c_d and exchange flows

Example application:
The Contact Theatre





To conclude

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Key advantages

- Ability to visualise real-time, 3D flows
- Ability to isolate and quantify specific flow phenomena

Key drawbacks

- Need specialist facility
- Difficult to recreate highly dynamic 'real' building scenarios, to capture daily building usage, weather conditions etc.

References

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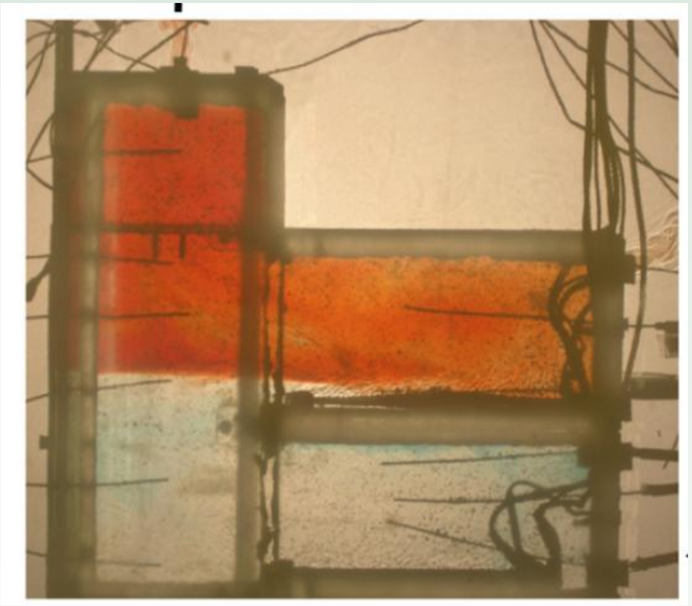

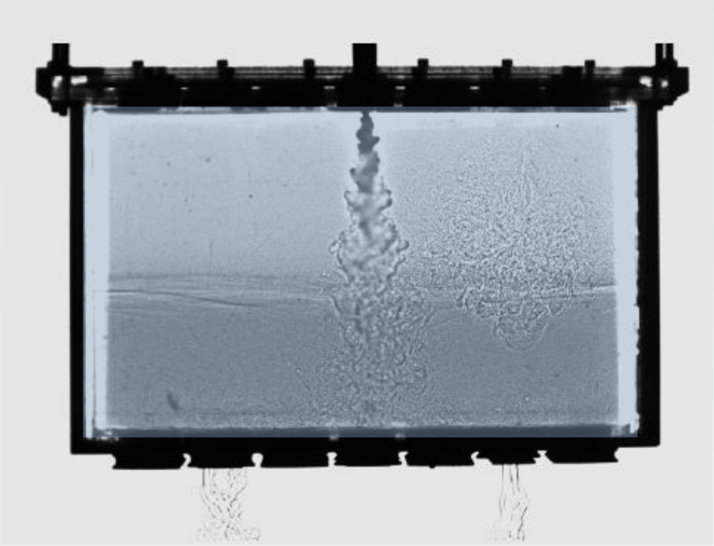

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