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Effects of ground heating on atmospheric gravity current fronts velocity

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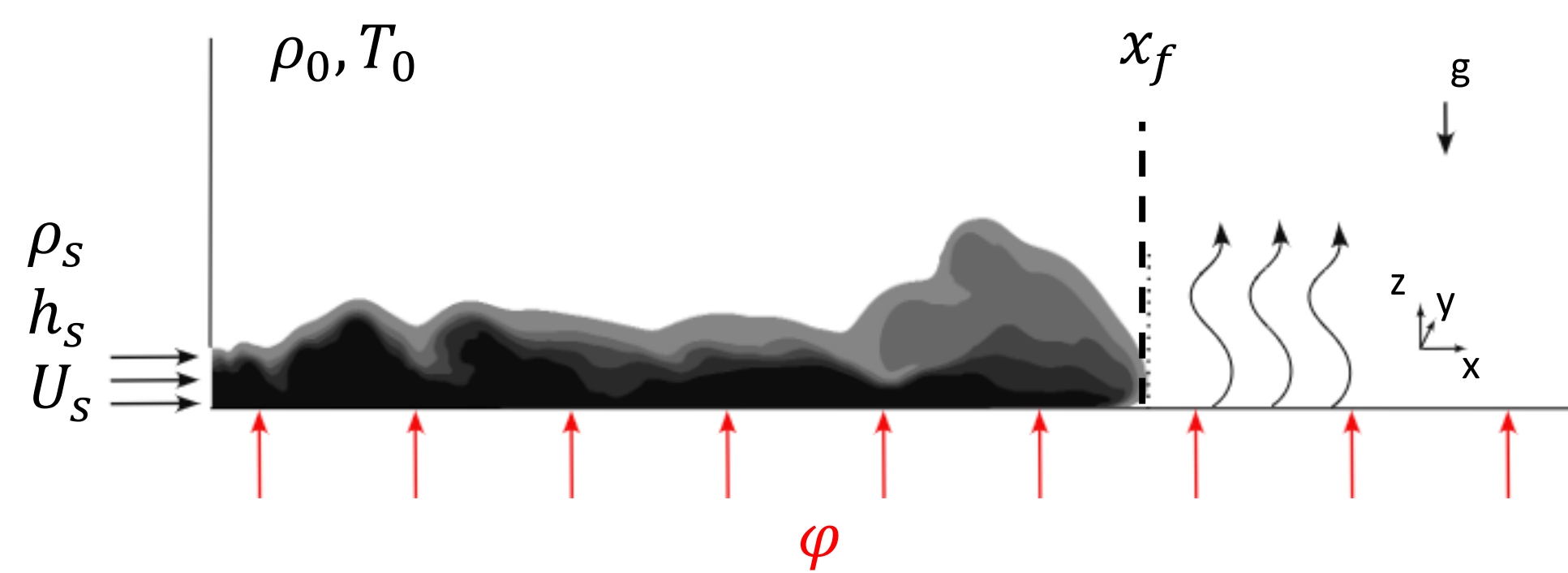
Objectives

The advancement of atmospheric gravity current fronts (e.g., thunderstorm outflows, sea breeze fronts) is influenced by the Earth's sensible heat flux. Simpson et al. 1977 [1] measured that sea breeze fronts travel over land more slowly at midday and accelerate in the evening, when surface heating is reduced. Other studies (e.g. Cenedese & Monti 2003 [2]) have shown that the structure of sea breeze fronts can be significantly altered when they interact with urban heat islands generated by cities. In this work, we present a laboratory study where atmospheric fronts are modeled as sustained gravity currents advancing over a heated surface. The objective is to investigate the scaling laws describing the front position as a function of time.



<https://www.theweathernetwork.com>

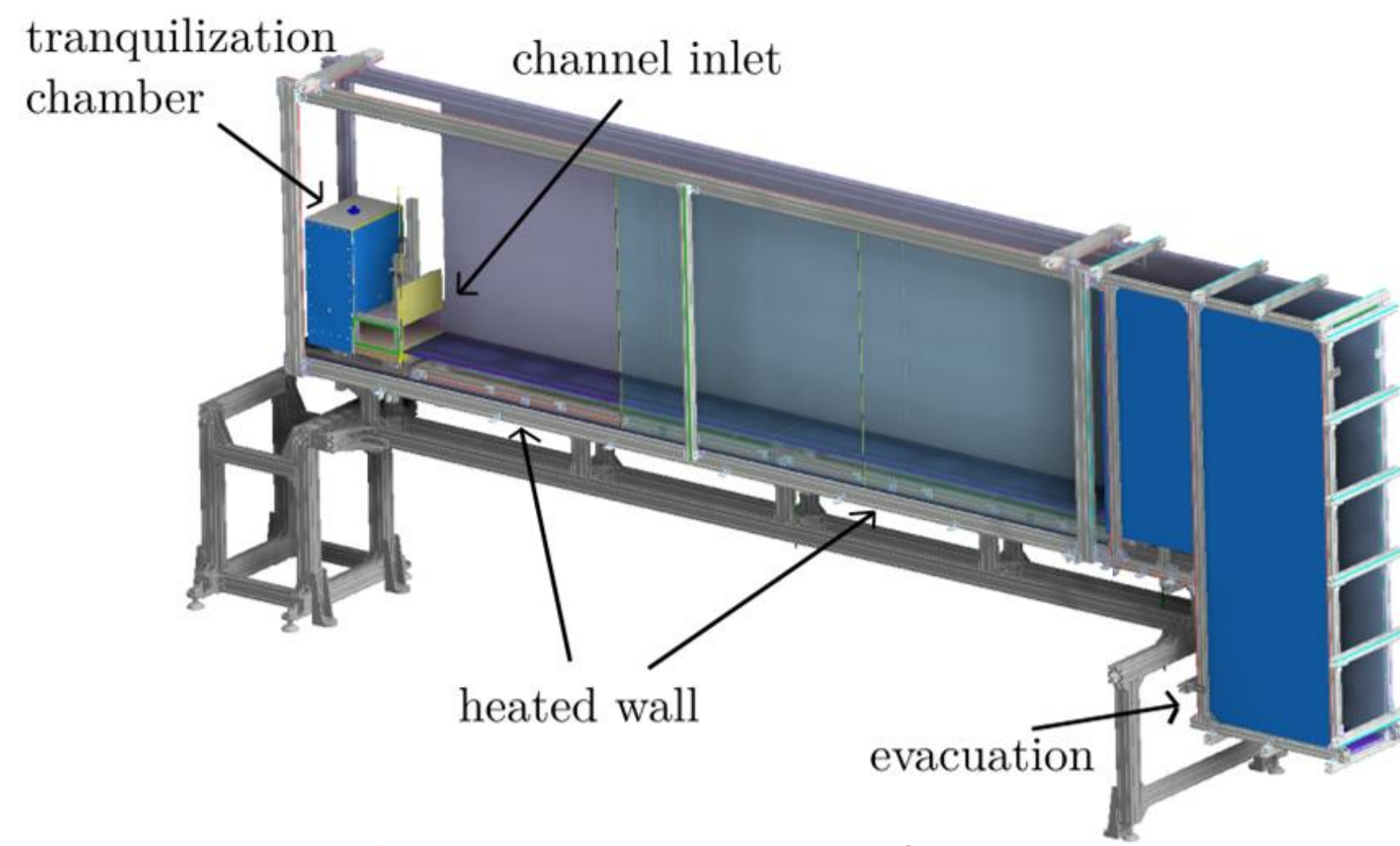
Governing Parameters



- U_s, h_s, ρ_s : inlet velocity, inlet height and inlet density
- φ : imposed heat flux per unit area
- ρ_0, T_0 : ambient density and temperature
- Richardson number at the source: $Ri_s = \frac{h_s g (\rho_s - \rho_0)}{U_s^2 \rho_0}$
- Horizontal buoyancy flux per unit length at the source: $B_s = U_s h_s \frac{g (\rho_s - \rho_0)}{\rho_0}$
- Vertical buoyancy flux per unit area induced by the heating φ : $B_\varphi = \frac{g \varphi}{c_p \rho_0 T_0}$

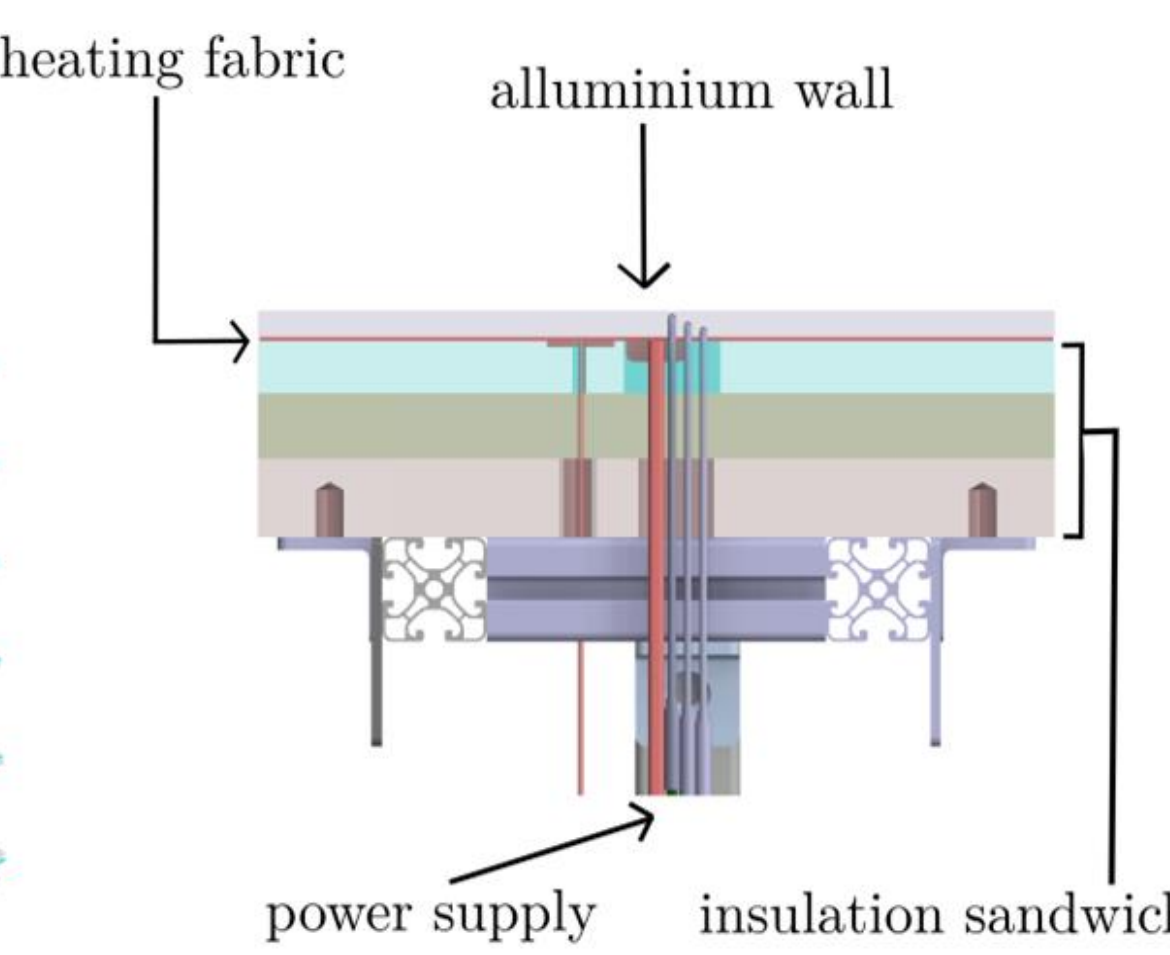
$$\frac{x_f}{h_s} = f\left(\frac{t B_s^{1/3}}{h_s}, Ri_s, \Lambda\right)$$

Experiments

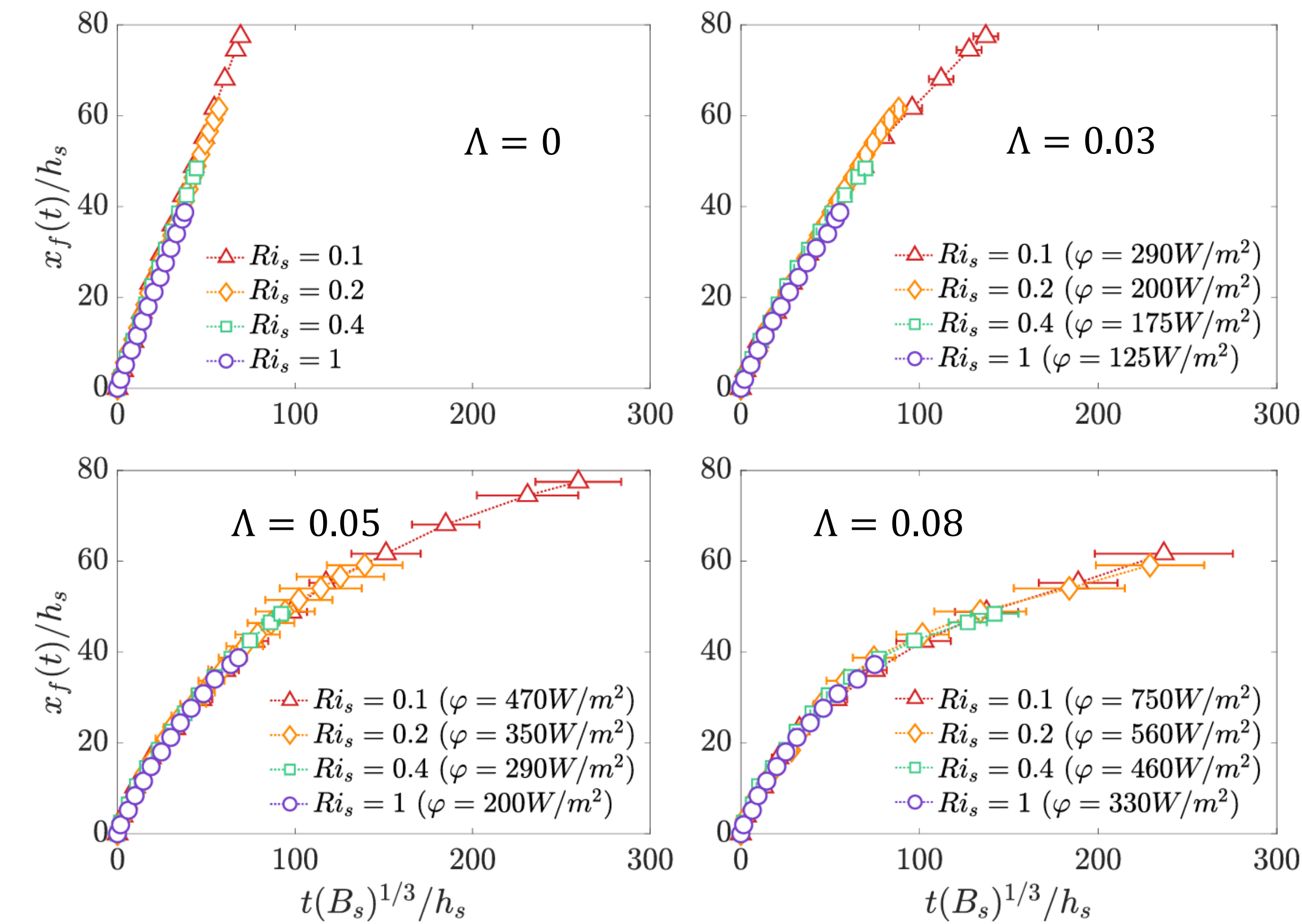


The experimental campaign is performed in a 4-meter-long rectangular channel, whose bottom wall can be warmed. The "sustained" gravity currents are generated by a mixture of air and CO₂ continuously supplied at the channel's inlet.

The current flow is visualized using laser tomography. Through video analysis, the position of the front can be determined as a function of time. The bottom surface over which the current propagates is heated by fabrics incorporating a uniformly distributed electrical resistance.



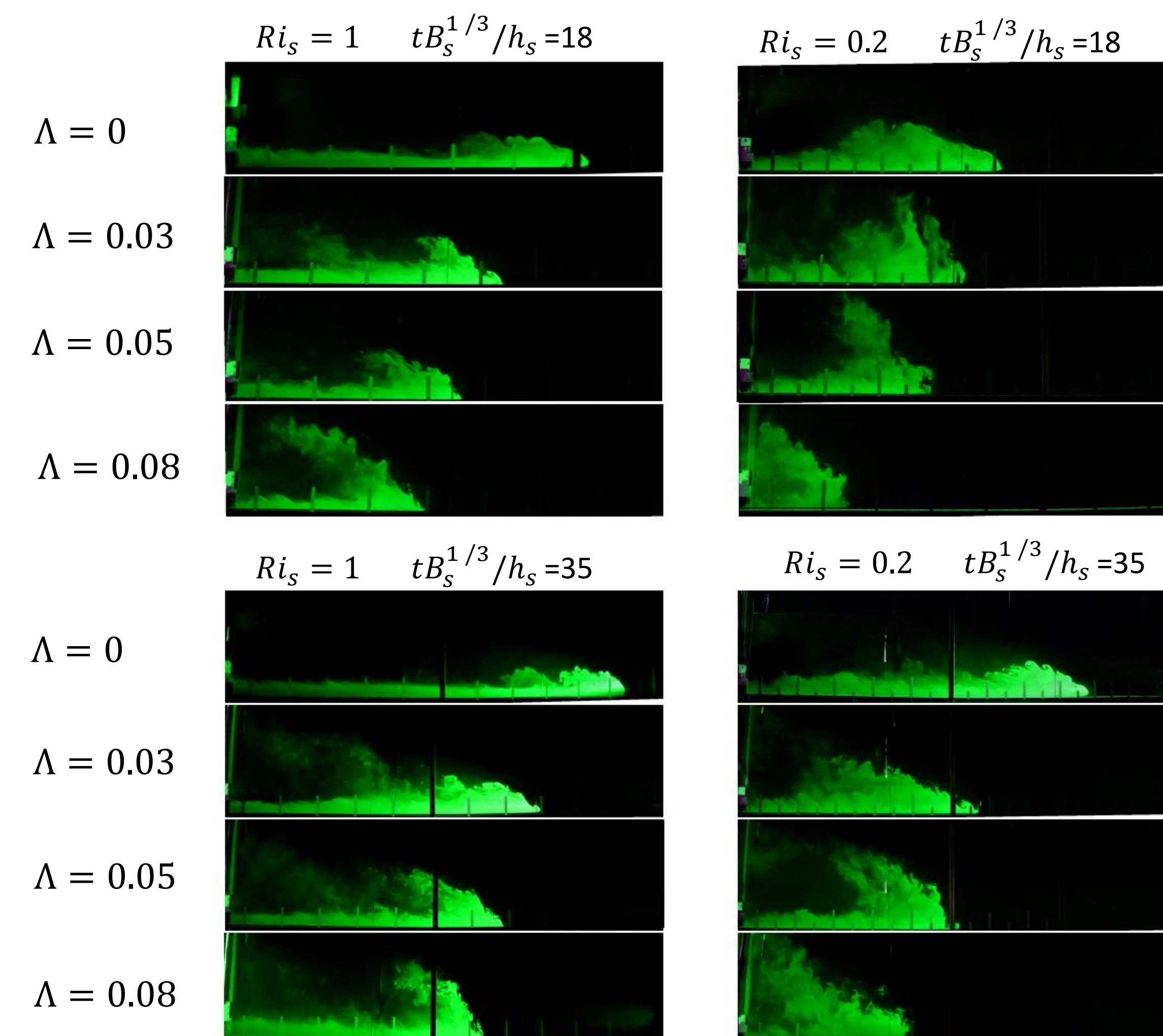
Results: Front Position



The Figure shows that Λ is the primary controlling parameter for the front velocity. The curves in the four plots are obtained with different values of B_s , h_s , and φ , but with a fixed Λ . Sufficiently close to the source, the front position as a function of time follows the power law:

$$\frac{x_f}{h_s} = \beta(Ri_s, \Lambda) \left(\frac{t B_s^{1/3}}{h_s}\right)^{\alpha(Ri_s, \Lambda)} \quad \text{for } x_f < x_c = \frac{3.2}{\Lambda}$$

Results: Flow Visualizations



The Figure displays snapshots of currents with $Ri_s = 1$ (left) and $Ri_s = 0.2$ (right), taken at two different time instants after the gate opening ($t B_s^{1/3}/h_s = 18$, top; and $t B_s^{1/3}/h_s = 35$, bottom) for various heating intensities. Increasing Λ (i.e., enhancing the heating intensity) results in a reduction in the propagation velocity of the front. This deceleration is caused by two distinct physical mechanisms:

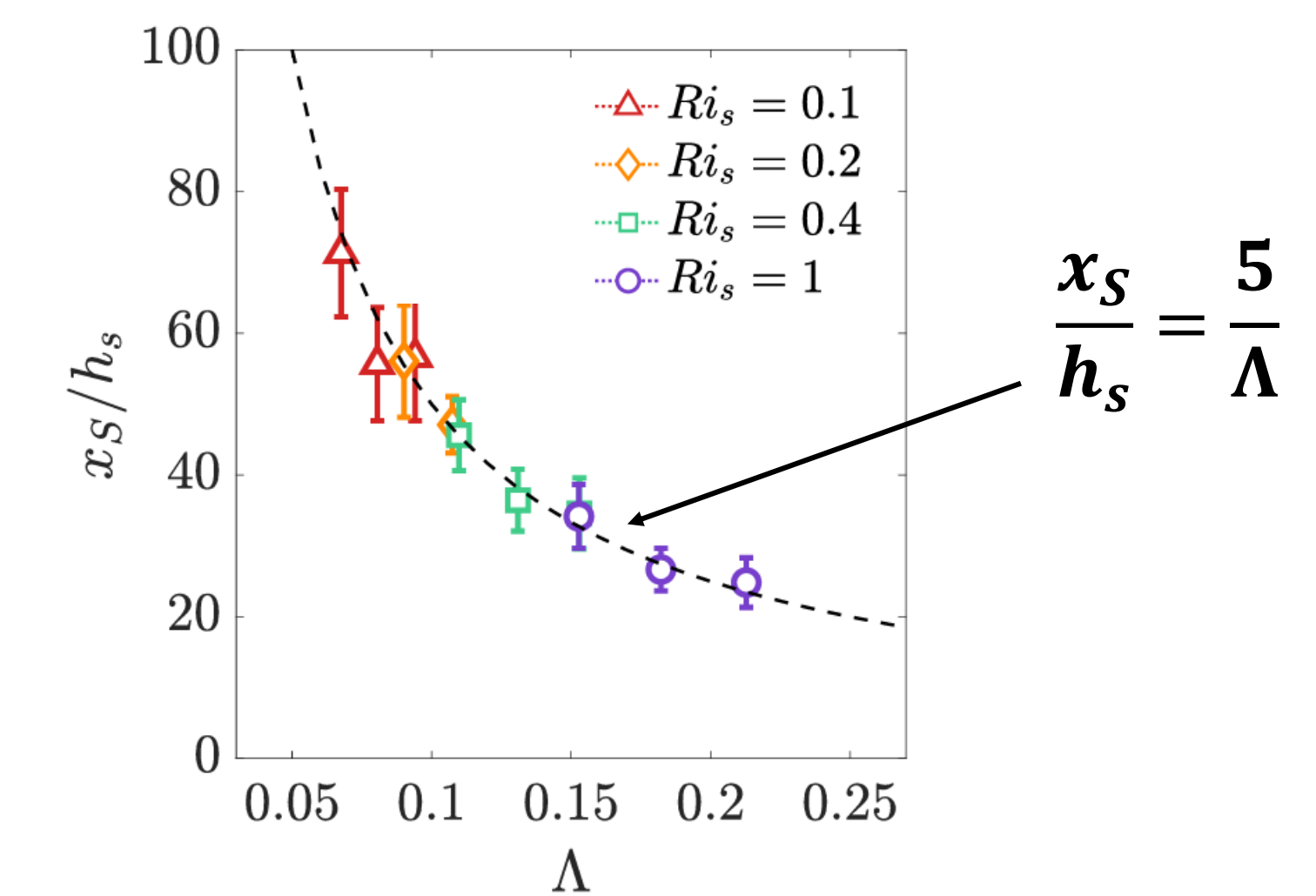
1. The interaction between the horizontal front and the **vertical thermal plumes** generated downstream of the current by natural convection. When the horizontal front encounters a vertical plume, a highly unstable situation that causes a strong increase in mixing intensity and head height is generated. The interaction with the thermal plumes increases the resistance to propagation.
2. The **direct heating of the current flow**. This leads to a reduction in the buoyancy flux at the current head, B . Indeed, dimensional analysis [3] shows that the front advancing velocity scales as $B^{1/3}$.

[Video with different heating intensities](#)

[Video of front stopped by strong heating](#)

Results: Stop Position

In experiments with sufficiently intense heating, the **advancing motion of the front is stopped**. In these cases, the heating of the current flow is so strong that the density difference between the head fluid and the air downstream of the front is canceled. The stop positions of the different experiments, for the range of conditions investigated in this study, **do not depend on the Richardson number at the source**.



Perspectives

- Extend the range of Λ and Ri_s considered in the investigation.
- Quantification of mixing intensity and entrainment coefficient.
- Experiments on steady heated currents with pointwise-simultaneous measurement of **velocity** (LDA), **CO₂ concentration** (FID), and **temperature** (cold wire).

References

- [1] Simpson, J. E., Mansfield, D. A. & Milford, J. R. 1977 Inland penetration of sea-breeze fronts. Quarterly Journal of the Royal Meteorological Society 103 (435), 47–76
- [2] Cenedese, A. & Monti, P. 2003 Interaction between an inland urban heat island and a sea-breeze flow: A laboratory study. Journal of Applied Meteorology 42 (11), 1569 – 1583
- [3] Sher, D. & Woods, A. W. 2017 Mixing in continuous gravity currents. Journal of Fluid Mechanics 818, R4.

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