Laboratory Experiments on Two Coalescing Axisymmetric Turbulent Plumes in a Rotating Fluid

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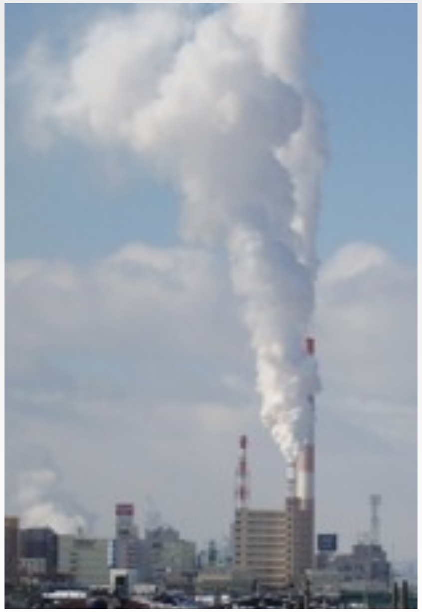
Introduction

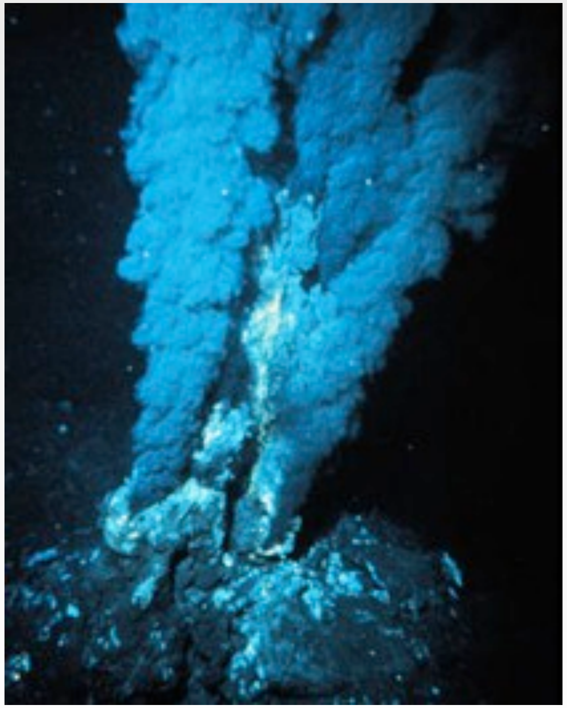
- There are many turbulent plumes at various scale.
  - Eruption of a volcano
  - Smoke from a chimney
  - Seafloor vents
  - etc.

Eruption of Miyakejima 2000



Smoke from a chimney (Tomakomai city)

Seafloor vents



movie of sea floor vents

http://oceanexplorer.noaa.gov/explorations/04fire/logs/april10/media/eifuku_champagne_video.html

movie of sea floor vents

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Summary of studies on the turbulent plumes and thermals

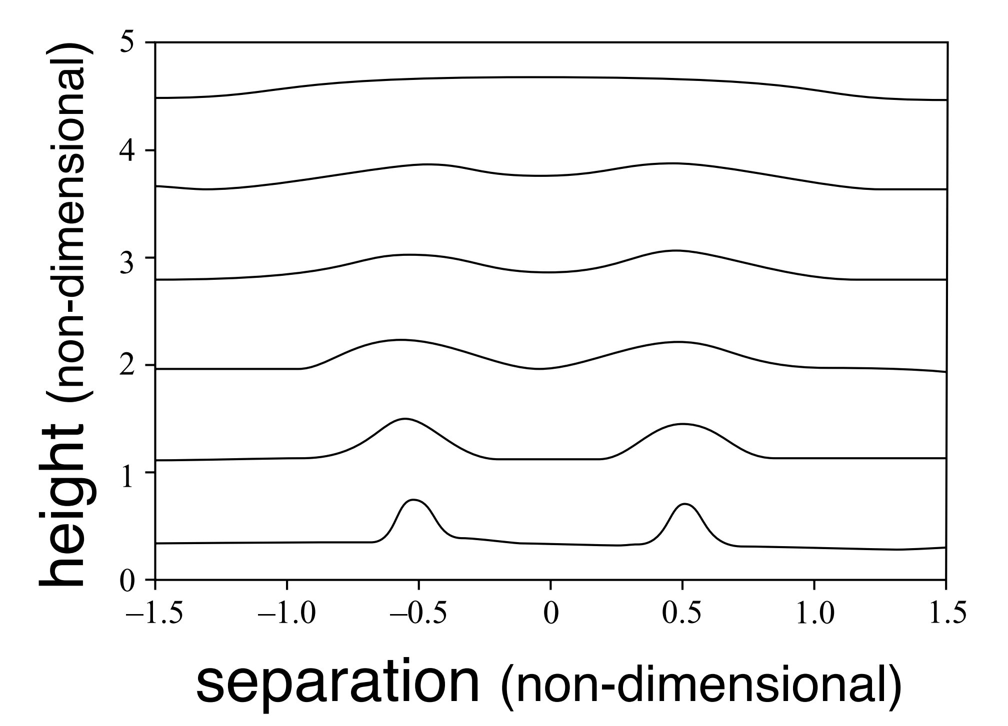
Ambient	Point source	Line source
Homogeneous	Morton, Taylor & Turner (1956) (P) Scorer (1957) (T) Johari (1992) (T)	Rouse, Yih & Humphreys (1952) (P) Richards (1963) (T)
Stratified	Morton, Taylor & Turner (1956) (P) Noh, Fernando & Ching (1992) (P) Ching, Fernando & Noh (1993) (P)	Wright & Wallace (1979) (P)
Rotating homogeneous	Elrick (1979) (T) Helfrich (1994) (T) Ayotte & Fernando (1994) (T) Fernando, Chen & Ayotte (1998) (P)	Fernando & Ching (1993) (P) Lavelle & Smith (1996) (P) Present study
Rotating stratified	Speer & Marshall (1995) (P) Helfrich & Battisti (1991) (P) Helfrich (1994) (T)	Present study

TABLE 1. Summary of studies on the dynamics of turbulent plumes (P) and thermals (T) in the presence of ambient stratification and/or rotation.

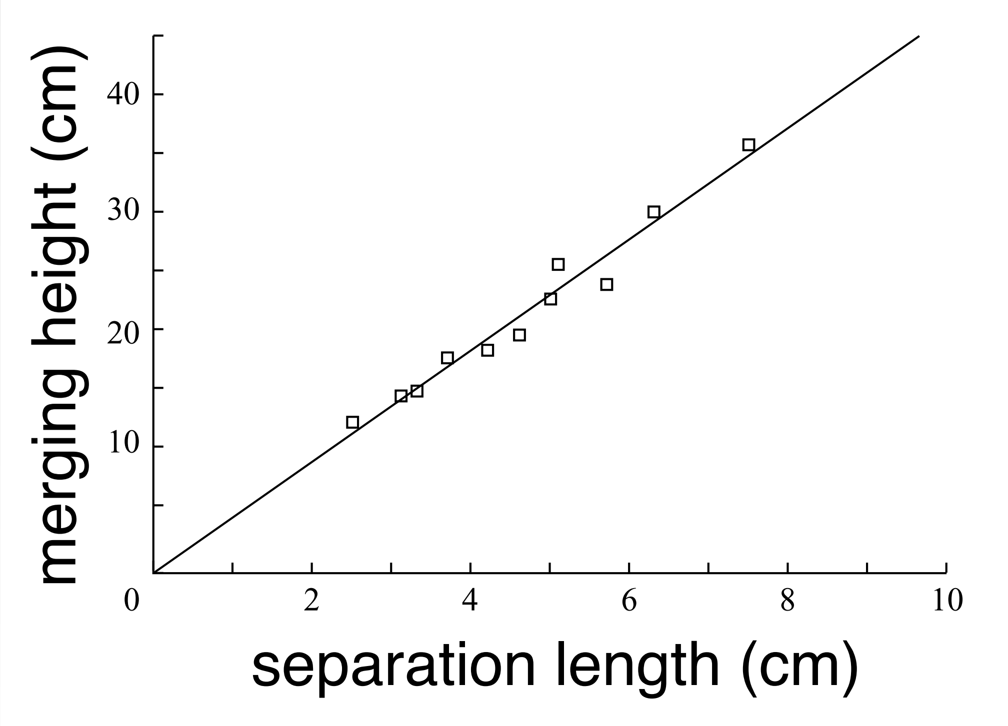
Bush and Woods (1999)

Motivation

- The problem of two coalescing axisymmetric turbulent plumes was studied by Kaye and Linden (2004).



Buoyancy profiles for two equal plumes showing their Gaussian profiles prior to merging, and the gradual coalescence.



Plume merging height for equal plumes plotted against initial separation.

Motivation (2)

- Kaye and Linden (2004) investigated two plumes in a **non-rotating**, **homogeneous** fluid.
- Helfrich and Battisti (1991) investigated the behavior of axisymmetric turbulent plumes in a **rotating, stratified** fluid.
- Fernando, Chen, and Ayotte (1998) investigated the evolution of a **single** turbulent plume in a **rotating homogeneous** fluid.

- What happens for **multiple plumes in a rotating, homogenous** fluid?

Experiments

✓Filling Tank experiment (Baines and Turner, 1969)

- to determine virtual origin height and entrainment constant

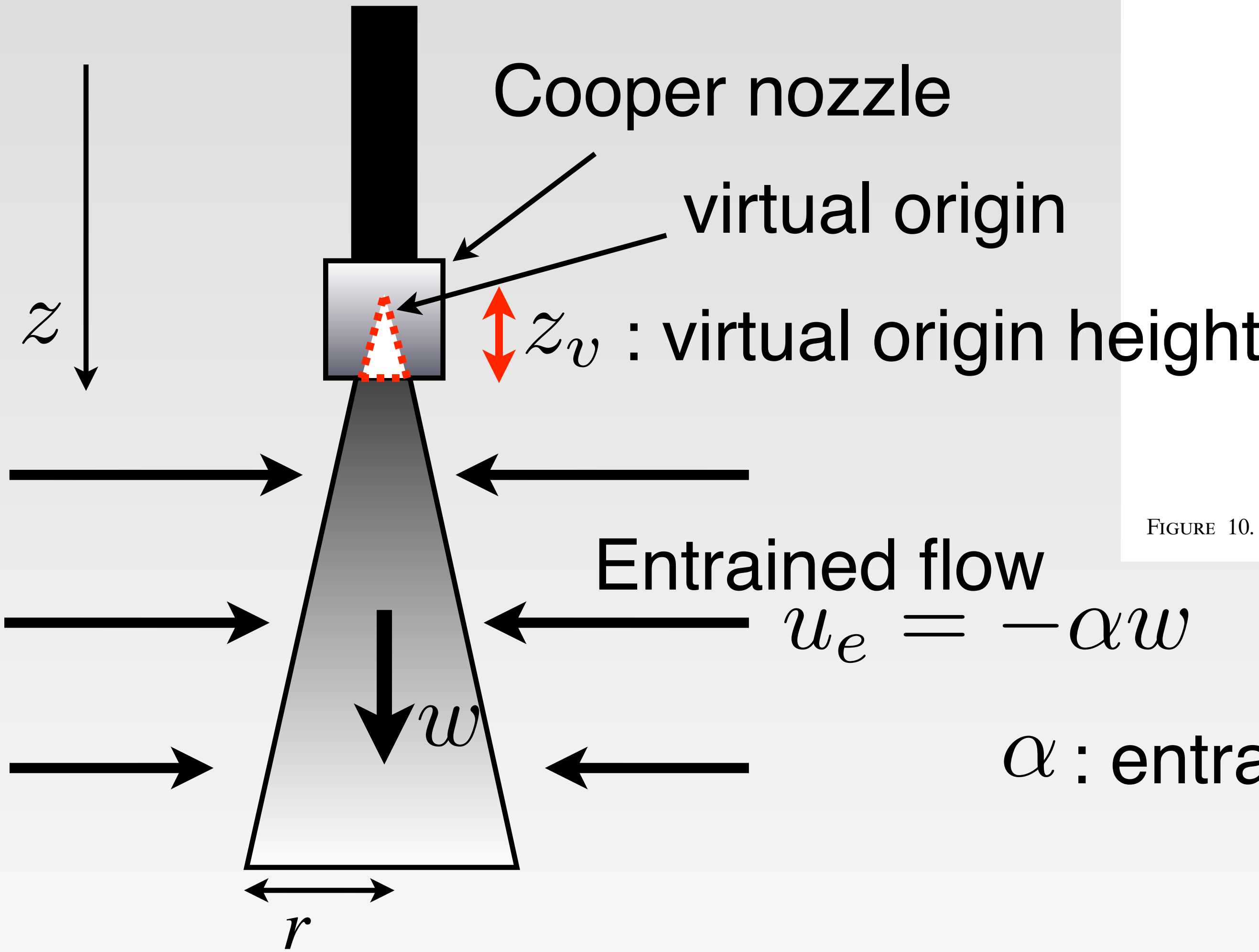
✓Two plumes experiments without rotation (Kaye and Linden, 2004)

- to verify the results of Kaye and Linden

✓Two plumes experiments with rotation

(All experiments were done with homogenous ambient fluid)

Axisymmetric Turbulent Plume



$$u_e = -\alpha w$$

α : entrainment constant

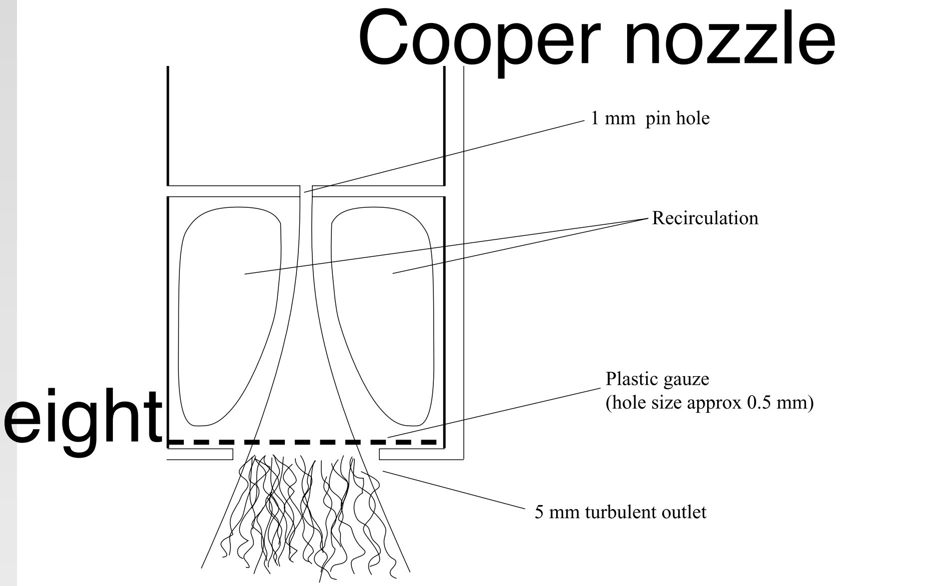
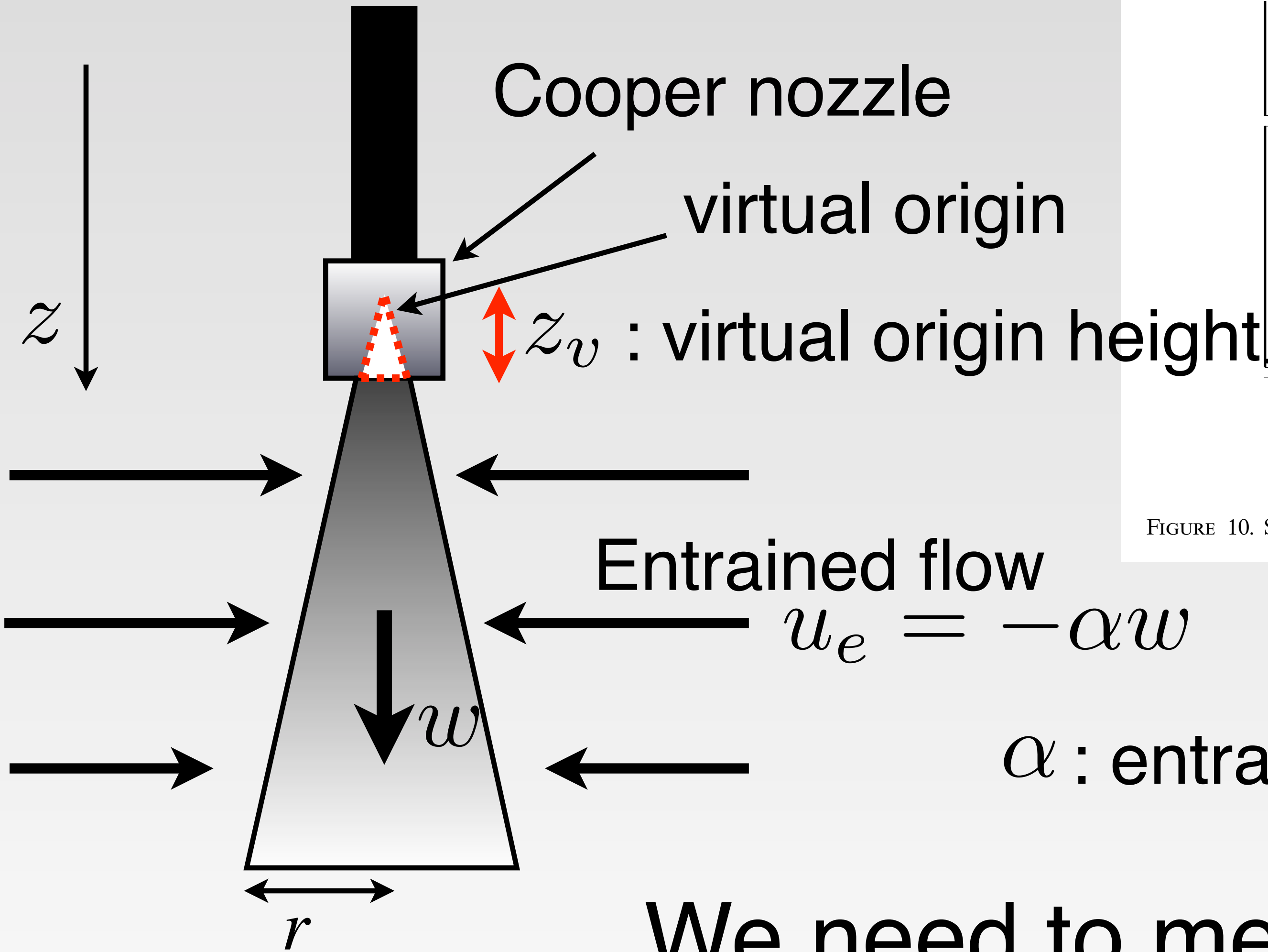


FIGURE 10. Schematic diagram of the Cooper plume nozzle used to produce a turbulent plume source.

Axisymmetric Turbulent Plume



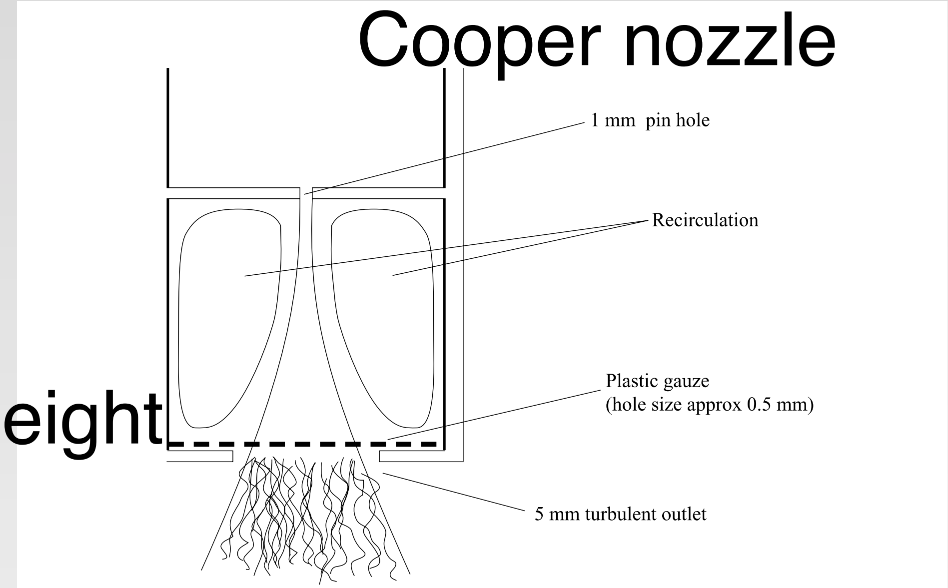


FIGURE 10. Schematic diagram of the Cooper plume nozzle used to produce a turbulent plume source.

$$u_e = -\alpha w$$

α : entrainment constant

We need to measure α and z_v

→ Filling Tank Experiment

(Baines and Turner, 1969)

General properties of an axisymmetric turbulent plume

- It is assumed that the profiles of vertical velocity w and buoyancy g' of the plume are of *Gaussian form*

$$
\begin{aligned}
w(z,r) &= W(z)\exp\left(-\frac{r^2}{b(z)^2}\right), \\
g'(z,r) &= g\left(\frac{\rho_A-\rho_P(z,r)}{\rho_R}\right) = G'(z)\exp\left(-\frac{r^2}{b(z)^2}\right).
\end{aligned}
$$

Here

$$W(z)=z(z,0), \quad G'(z)=g'(z,0)$$

$b(z)$ is the radius where they reduced by a factor $1/e$ from those on the plume axis.

Volume flux Q

$$Q = \int_0^{2\pi} \int_0^{\infty} wrdrd\theta = \pi b^2 W$$

Volume flux Q

$$Q = \int_0^{2\pi} \int_0^{\infty} w r dr d\theta = \pi b^2 W$$

Momentum flux M

$$M = \int_0^{2\pi} \int_0^{\infty} w^2 r dr d\theta = \frac{\pi}{2} b^2 W^2$$

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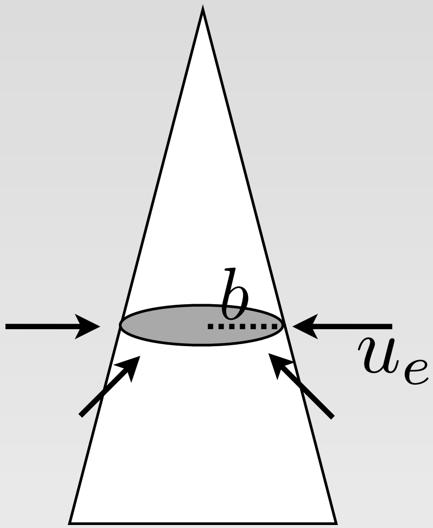
Momentum flux M

$$M = \int_0^{2\pi} \int_0^{\infty} w^2 rdrd\theta = \frac{\pi}{2} b^2 W^2$$

Buoyancy flux F

$$F = \int_0^{2\pi} \int_0^{\infty} g' wrdrd\theta = \frac{G'}{2} Q$$

- Volume flux Q increase with z, because of entrainment



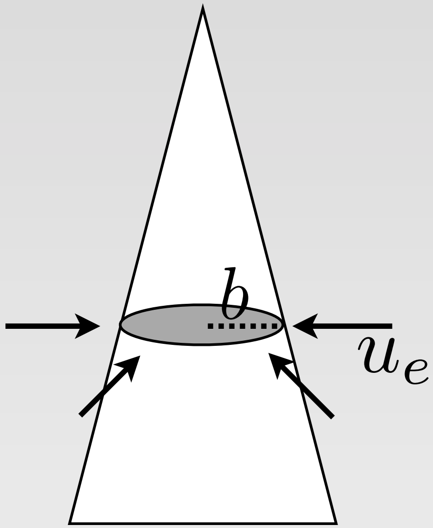
$$
\begin{aligned}
\frac{\partial Q}{\partial z} &= -2\pi b u_e, \\
&= 2\pi\alpha b w, \\
&= 2\sqrt{2}\pi^{\frac{1}{2}}\alpha M^{\frac{1}{2}}.
\end{aligned}
$$

entrained flow

$$u_e = -\alpha w$$

entrainment constant

- Volume flux Q increase with z, because of entrainment



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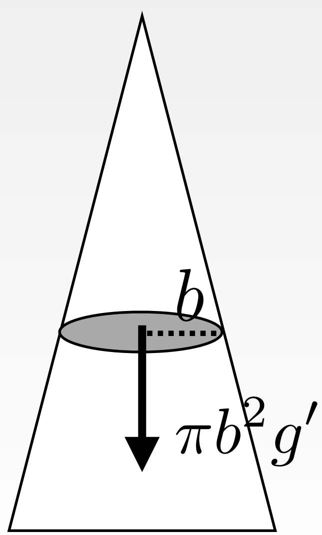
entrained flow

$$u_e = -\alpha w$$

entrainment constant

- Momentum flux M increase with z, because of reduced gravity



$$
\begin{aligned}
\frac{\partial M}{\partial z} &= \pi b^2 g', \\
&= \frac{(\pi g' b^2 w)/2 \cdot \pi b^2 w}{(\pi b^2 w^2)/2}, \\
&= \frac{FQ}{M}.
\end{aligned}
$$

- We can set $F = F_0$, because the entrainment not only decrease the buoyancy g' but also increase the volume flux Q.
- Therefore the equation of dQ/dz and dM/dz can be written as

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\frac{\partial Q}{\partial z} &= 2\sqrt{2}\pi^{\frac{1}{2}}\alpha M^{\frac{1}{2}}, \\
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$$\begin{aligned} \frac{\partial Q}{\partial z} &= 2\sqrt{2}\pi^{\frac{1}{2}}\alpha M^{\frac{1}{2}}, \\ \frac{\partial M}{\partial z} &= \frac{F_0 Q}{M}. \end{aligned}$$

- Now we assume

$$\begin{aligned} Q &= Q_0(z+z_V)^q, \\ M &= M_0(z+z_V)^m, \end{aligned}$$

(note: $z=0$ is the height of nozzle and $z=-z_V$ is virtual origin)

$$
\begin{aligned}
Q_0 q (z + z_V)^{q-1} &= 2\sqrt{2}\pi^{\frac{1}{2}} \alpha M_0^{\frac{1}{2}} (z + z_V)^{\frac{m}{2}}, \\
M_0 m (z + z_V)^{m-1} &= \frac{F_0 Q_0}{M_0} (z + z_V)^{q-m}.
\end{aligned}
$$

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\end{aligned}
$$

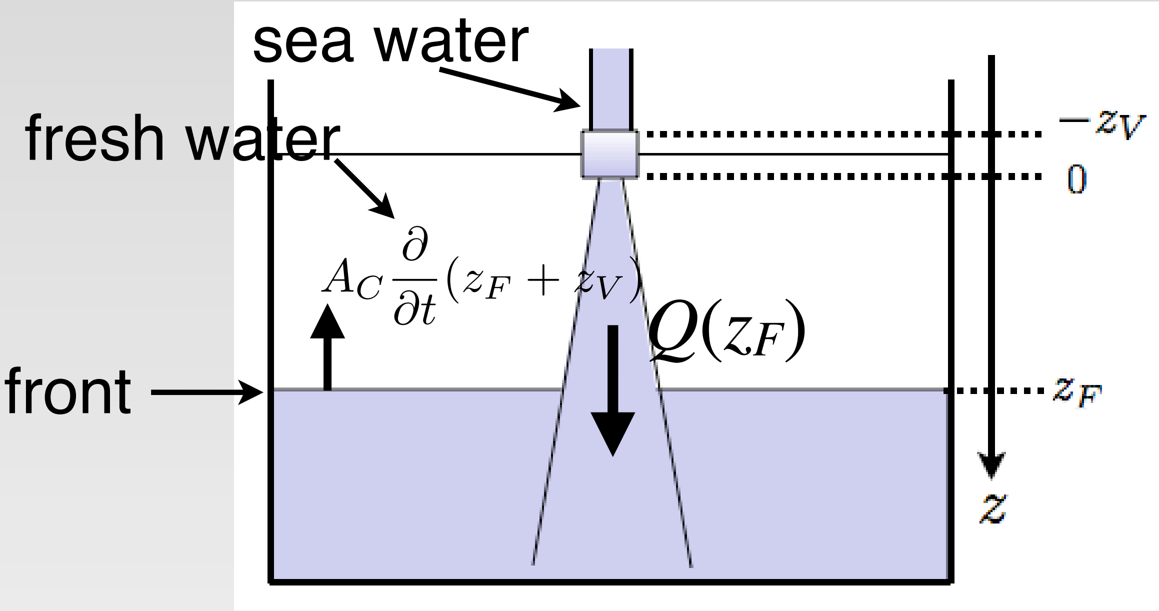
- and then, we obtain

$$
\begin{aligned}
q &= \frac{5}{3}, \\
m &= \frac{4}{3}.
\end{aligned}
$$

- and

$$
\begin{aligned}
M_0 &= \left(\frac{9\sqrt{2}\pi^{\frac{1}{2}}\alpha F_0}{10}\right)^{\frac{2}{3}}, \\
Q_0 &= \frac{6\pi^{\frac{1}{2}}\alpha}{5}\left(\frac{18\pi^{\frac{1}{2}}\alpha F_0}{5}\right)^{\frac{1}{3}}.
\end{aligned}
$$

Filling tank experiment

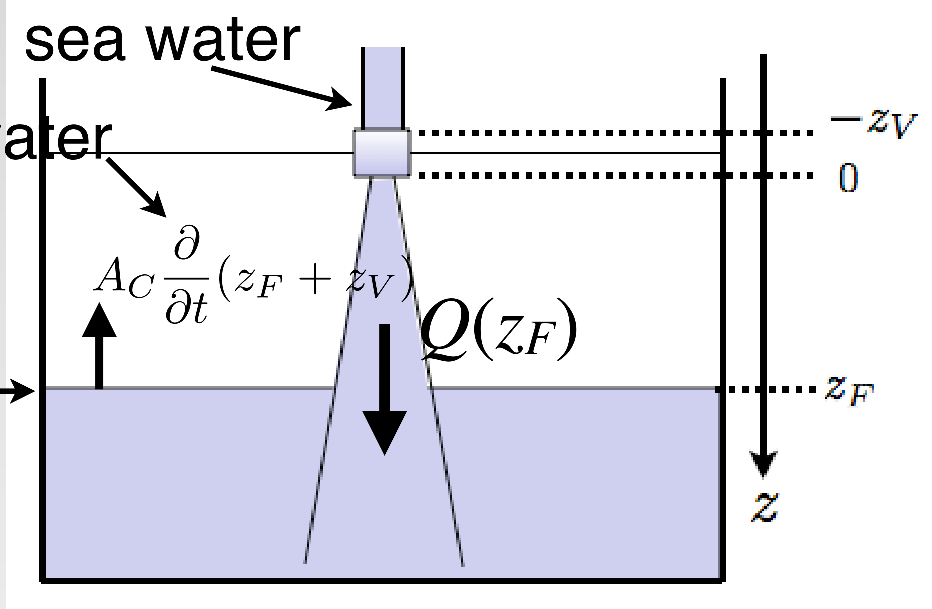


z_F: height of the front of colored sea water

A_C: cross section of the tank

$$
\begin{aligned}
\frac{\partial}{\partial t}(z_F(t) + z_V) &= -\frac{Q(z_F)}{A_C}, \\
&= -\frac{Q_0}{A_C}(z_F + z_V)^{\frac{5}{3}}.
\end{aligned}
$$

Filling tank experiment



z_F: height of the front of colored sea water

A_C: cross section of the tank

$$\begin{aligned} \frac{\partial}{\partial t}(z_F(t) + z_V) &= -\frac{Q(z_F)}{A_C}, \\ &= -\frac{Q_0}{A_C}(z_F + z_V)^{\frac{5}{3}}. \end{aligned}$$

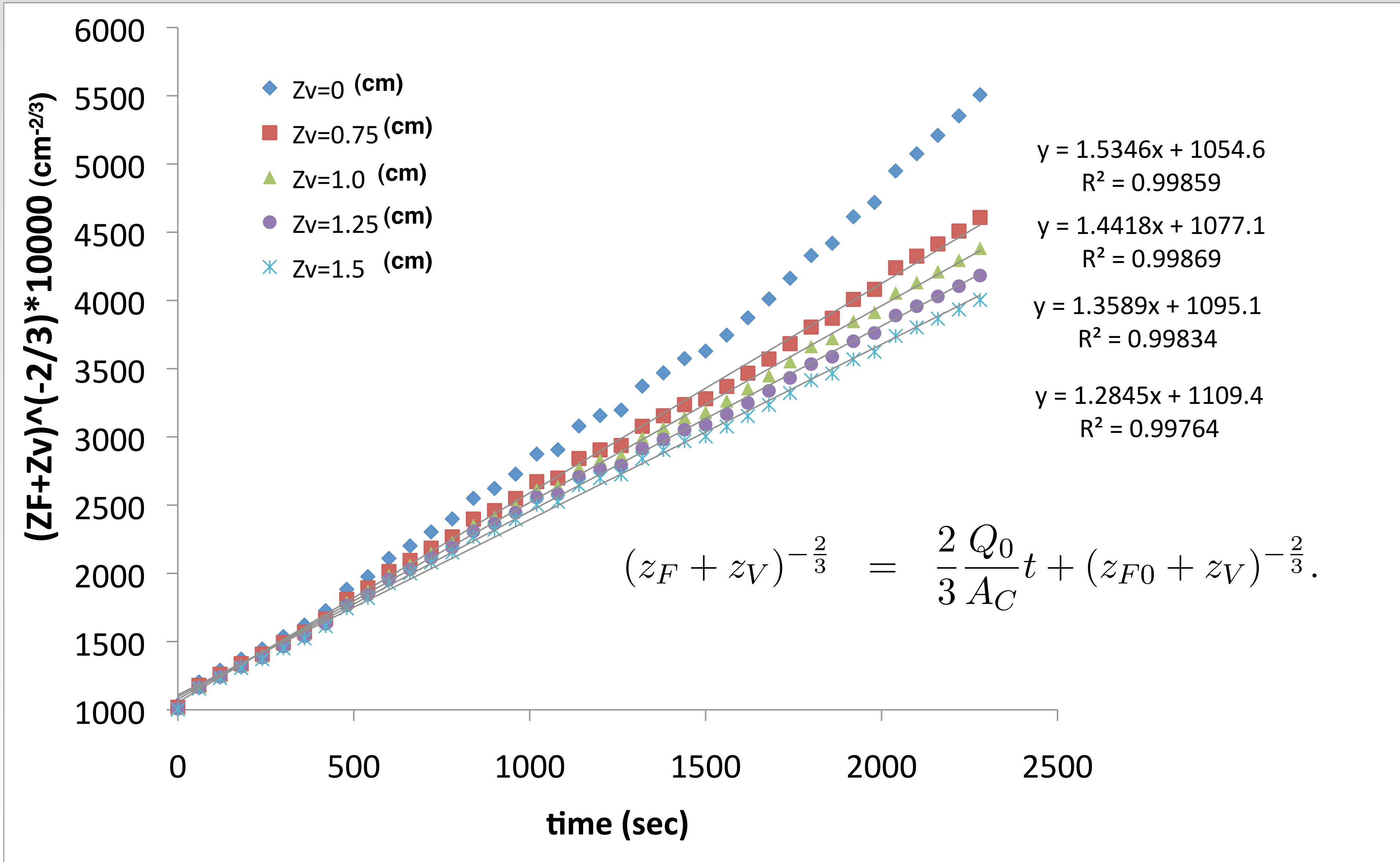
Integrating this equation, we obtain

$$(z_F + z_V)^{-\frac{2}{3}} = \frac{2}{3}\frac{Q_0}{A_C}t + (z_{F0} + z_V)^{-\frac{2}{3}}.$$

Here z_{F0} is the height when we start measuring z_F and we set that time $t = 0$

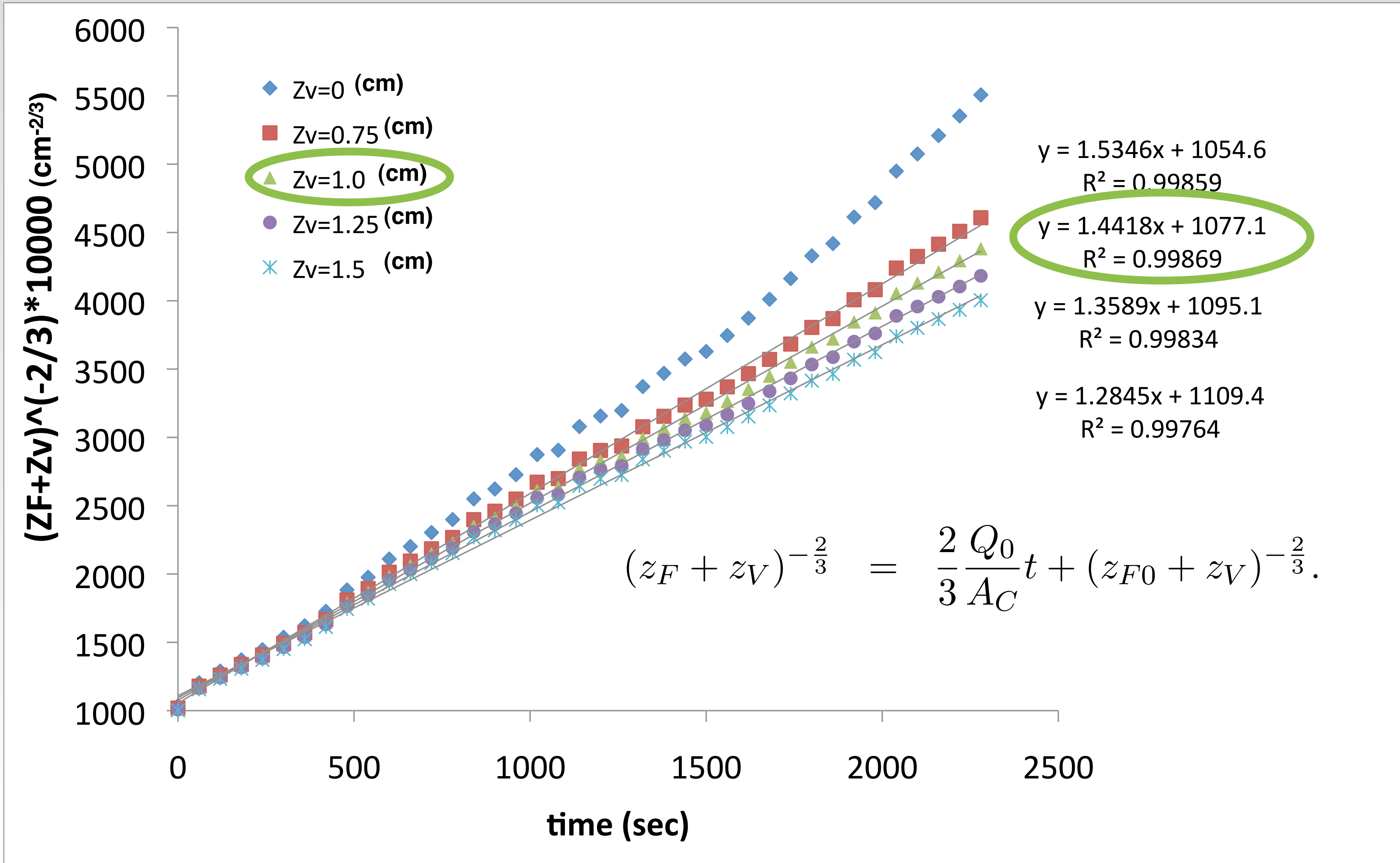
Filling tank experiment

- A_C = 60 × 60 cm^2, F_0 = 42 cm^4/s^3



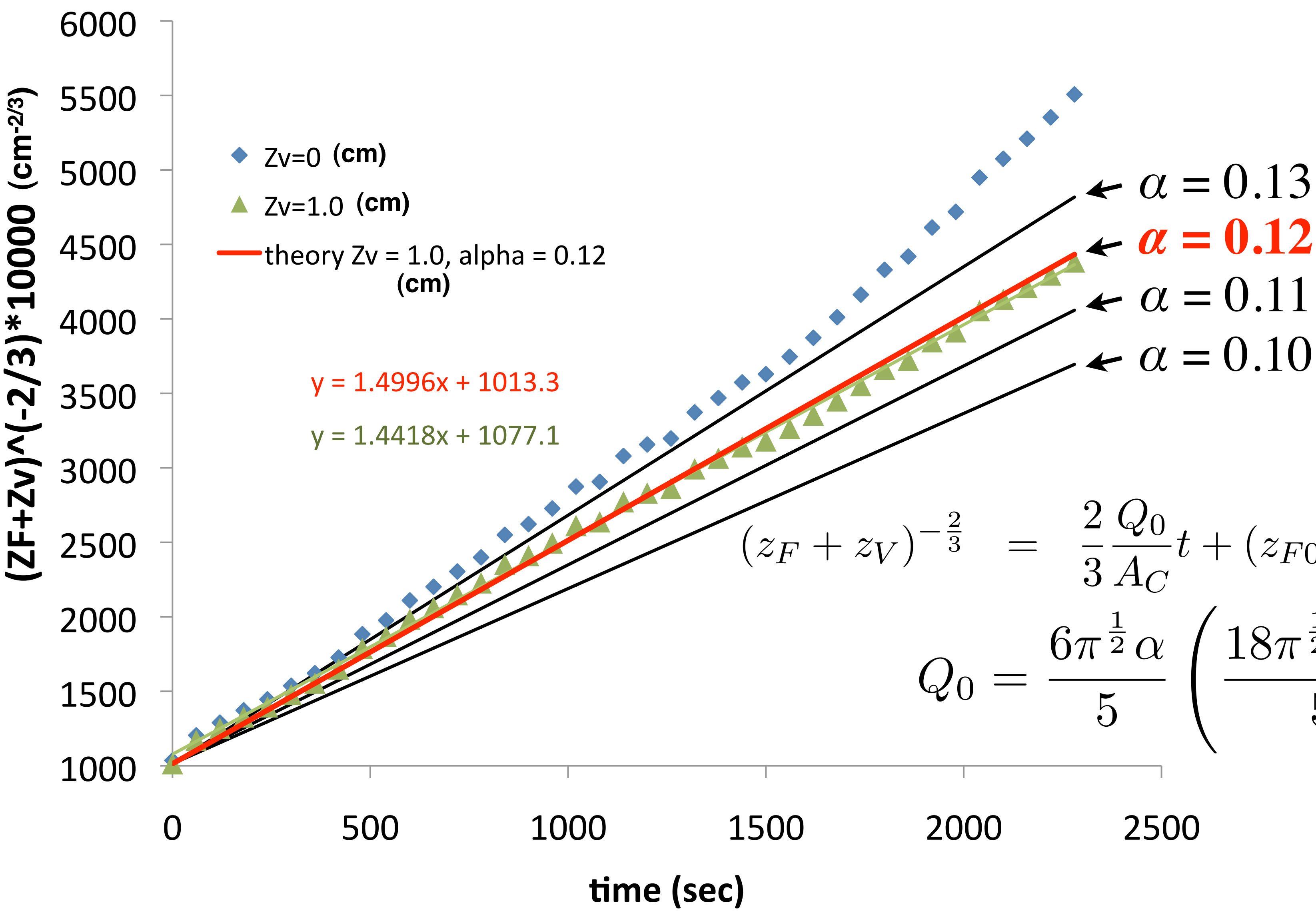
Filling tank experiment

- A_C = 60 × 60 cm², F_0 = 42 cm⁴/s³



$$(z_F + z_V)^{-\frac{2}{3}} = \frac{2}{3}\frac{Q_0}{A_C}t + (z_{F0} + z_V)^{-\frac{2}{3}}.$$

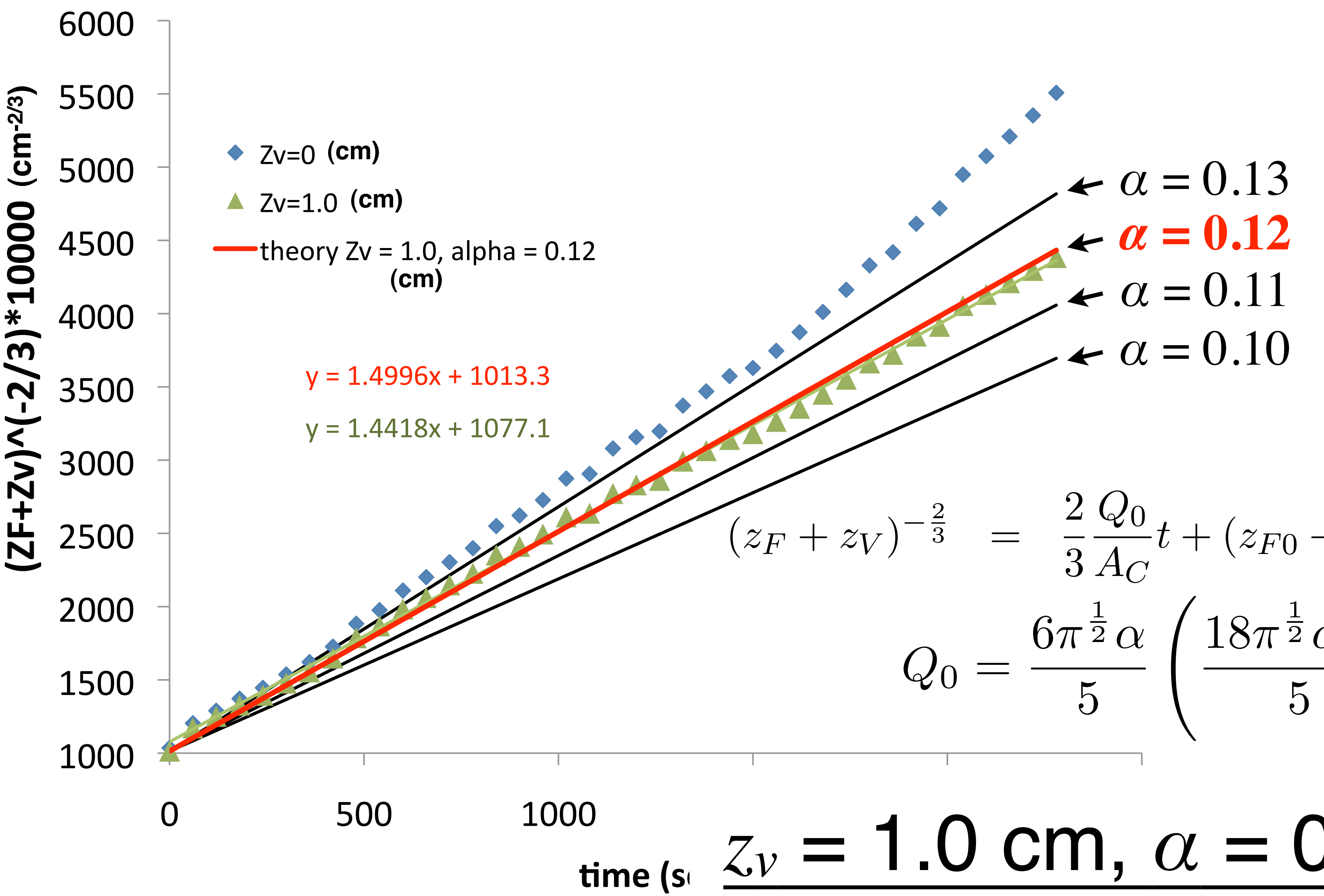
Filling tank experiment



$$(z_F + z_V)^{-\frac{2}{3}} = \frac{2}{3}\frac{Q_0}{A_C}t + (z_{F0} + z_V)^{-\frac{2}{3}}.$$

$$Q_0 = \frac{6\pi^{\frac{1}{2}}\alpha}{5}\left(\frac{18\pi^{\frac{1}{2}}\alpha F_0}{5}\right)^{\frac{1}{3}}$$

Filling tank experiment



$$(z_F + z_V)^{-\frac{2}{3}} = \frac{2}{3}\frac{Q_0}{A_C}t + (z_{F0} + z_V)^{-\frac{2}{3}}.$$

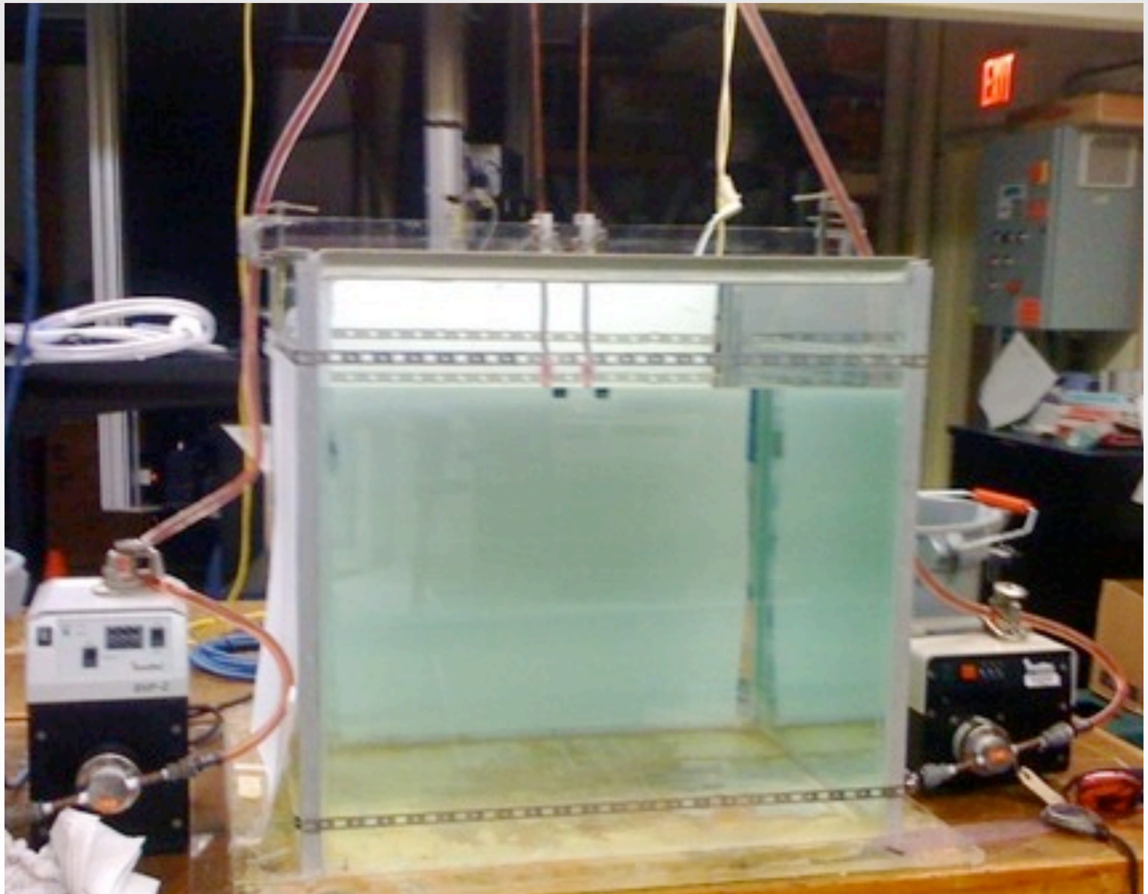
$$Q_0 = \frac{6\pi^{\frac{1}{2}}\alpha}{5}\left(\frac{18\pi^{\frac{1}{2}}\alpha F_0}{5}\right)^{\frac{1}{3}}$$

z_v = 1.0 cm, α = 0.12

Two plume experiments without rotation

Two plumes experiments without rotation

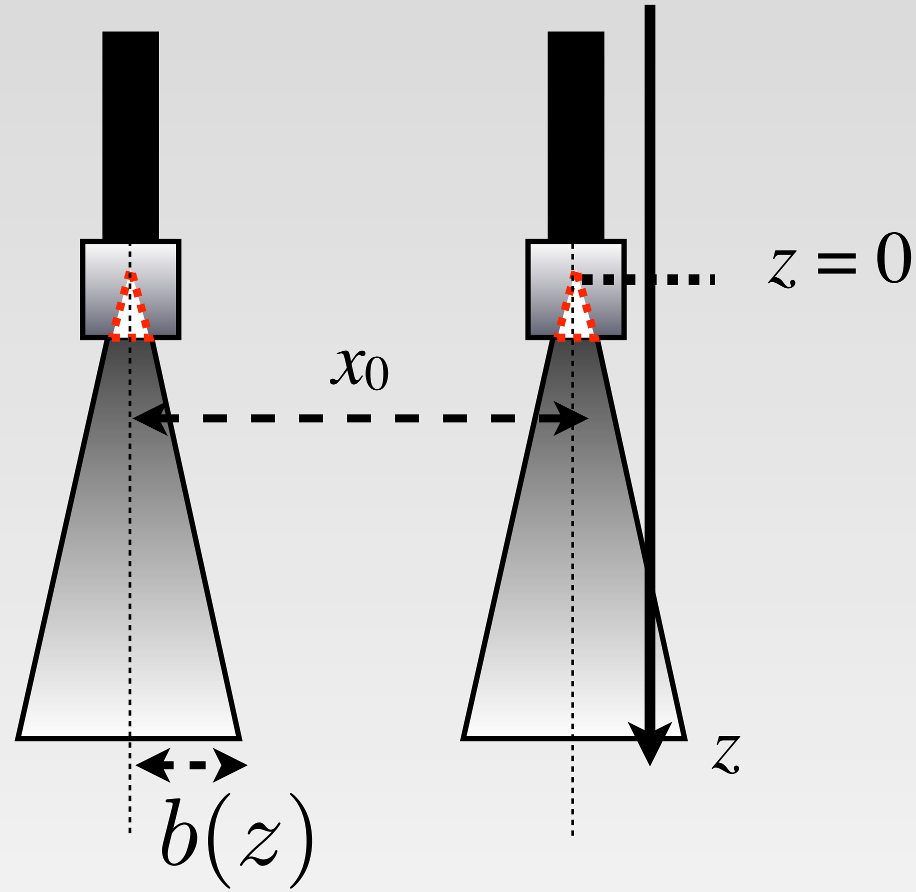
- Before performing rotating experiments, I carried out two plumes experiments without rotation to verify the theory and results of Kaye and Linden (2004).



Theory of Kaye and Linden

- Define variables as right figure.
- Consider two equal plumes with origin at the same height.
- The average buoyancy profile of a single turbulent plume can be taken as Gaussian, with a radius given by

$$b(z) = \frac{1}{\sqrt{2}}\pi^{-\frac{1}{2}}\frac{Q}{M^{\frac{1}{2}}} = \frac{6}{5}\alpha z$$



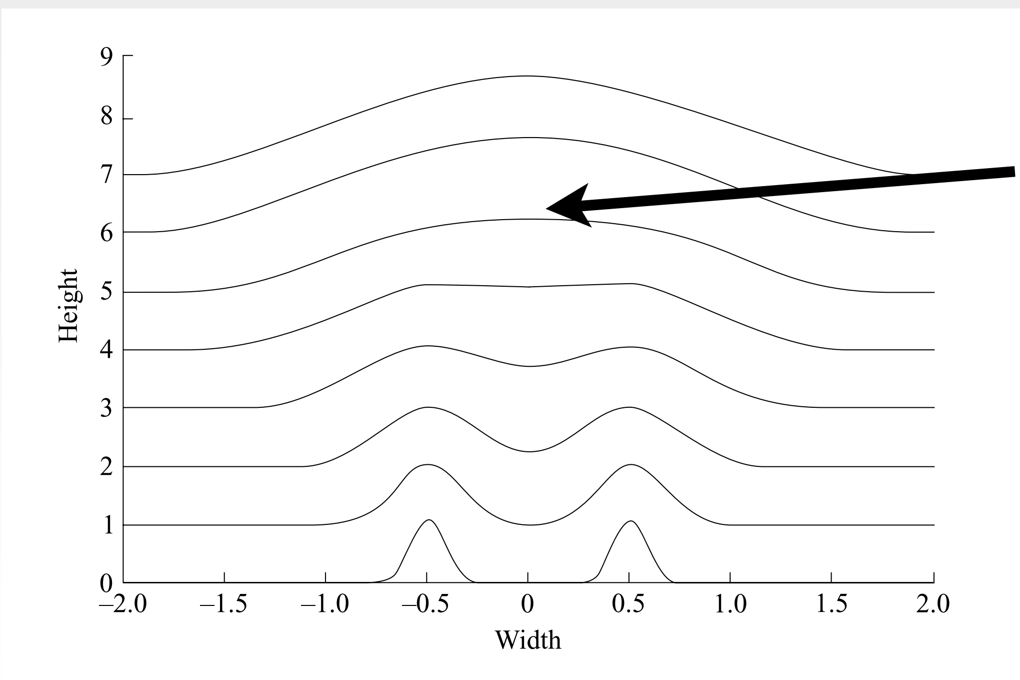
If plumes do not interact

- buoyancy profile function is given by

$$g'(r,z) = G'(z)E(r)$$

$$E(r) = \exp\left[-\frac{(r-\frac{1}{2}x_0)^2}{b^2}\right] + \exp\left[-\frac{(r+\frac{1}{2}x_0)^2}{b^2}\right]$$

Here, r is the radial distance from the center of the two plume axis



define merging height at when

$$\frac{d^2E}{dr^2} = 0 \quad \text{at} \quad r = 0$$

- For non-interacting plumes,

$$\frac{d^2E}{dr^2} = 0 \quad \text{at} \quad r = 0$$

can be easily solved to give

$$b_m = \frac{1}{\sqrt{2}} x_0$$

where subscript m denotes the value at the merging height

- Using $b=6\alpha w/5$, we obtain

$$z_m = \frac{1}{\sqrt{2}} \frac{5}{6\alpha} x_0$$

It is shown that this estimate is poor (Bjorn and Neilsen, 1995)

Plumes interact

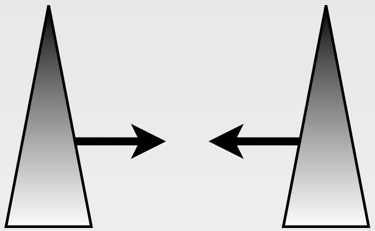
- Based on experimental results (Rouse, Yih and Humpherys, 1952) it is reasonable to take the velocity field outside the plumes created by entrainment as horizontal.
- Along the line of the plumes, the velocity is given by

$$U_{\theta=0} = -b\alpha w \left(\frac{1}{r + \frac{1}{2}x} + \frac{1}{r - \frac{1}{2}x} \right).$$

On the plume axis, the value of horizontal entrainment velocity due to that plume is zero. Therefore, the mean horizontal velocity u on the plume axis is

$$u = -\frac{b\alpha w}{x}$$

- Assuming that each plume is passively advected by the entrainment field of the other,
- the rate of change of separation with height will be given by the vertical to horizontal velocities at the plume axis.
- As both plumes are deflected equally, the rate is



$$\frac{dx}{dz} = -2\frac{1}{w}\frac{b\alpha w}{x}$$

Substituting $b=6\alpha w/5$, and integrate from $z=0$ to $z=z_m$

$$\int_{x_0}^{x_m} dx = -\frac{12}{5}\alpha^2 \int_0^{z_m} dz$$

$$x_0^2 = \frac{12}{5}\alpha^2 z_m^2 + x_m^2$$

- Now we use the relation between z and x

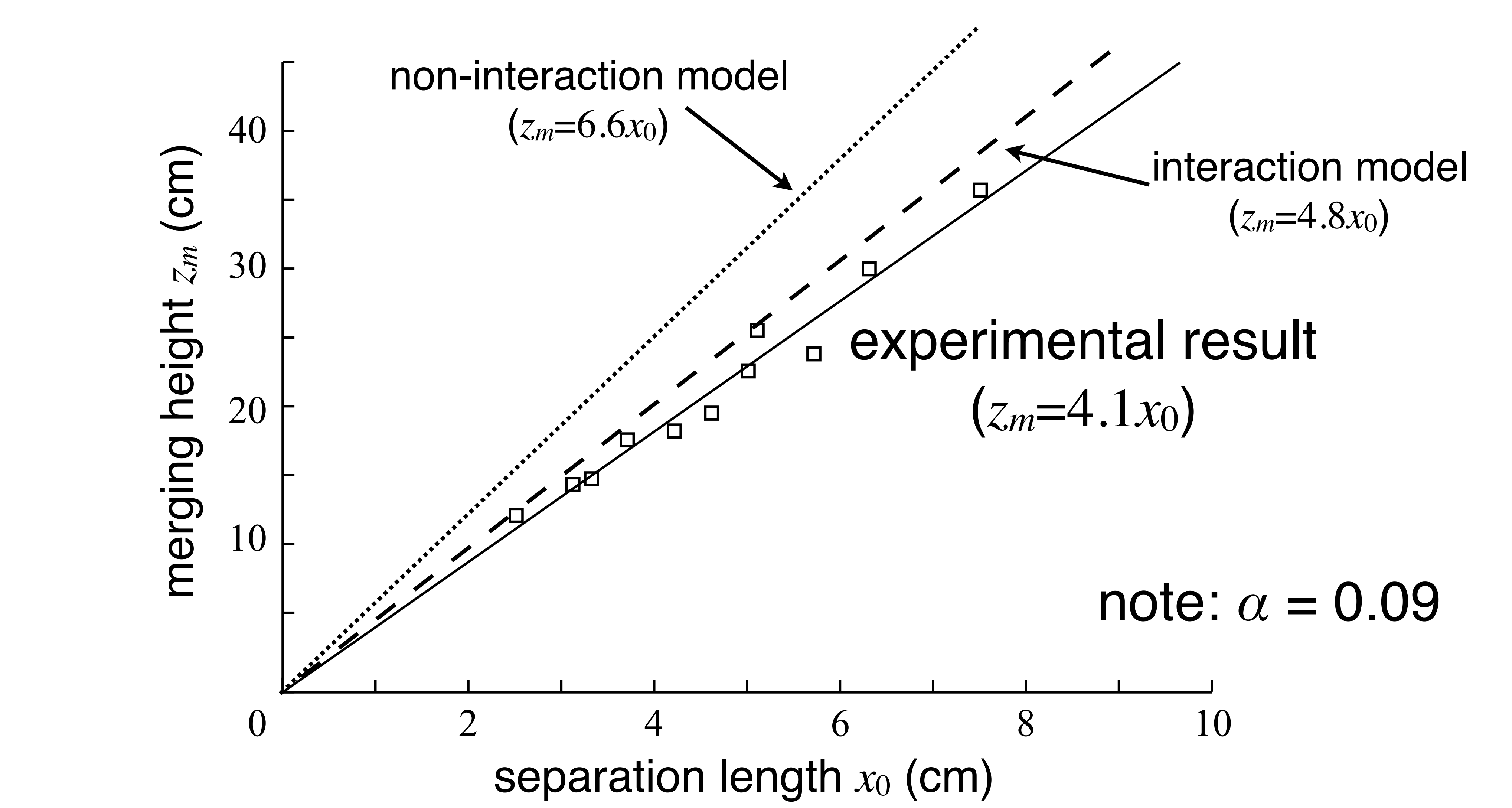
$$x_m = \frac{6\sqrt{2}\alpha}{5} z_m$$

which we derived for the non-interacting model. (It is appropriate here because we assumed that plumes are passively advected only.)

Then we obtain

$$\frac{z_m}{x_0} = \frac{1}{\alpha}\sqrt{\frac{25}{132}} \approx \frac{0.44}{\alpha}$$

Results of Kaye and Linden (2004)

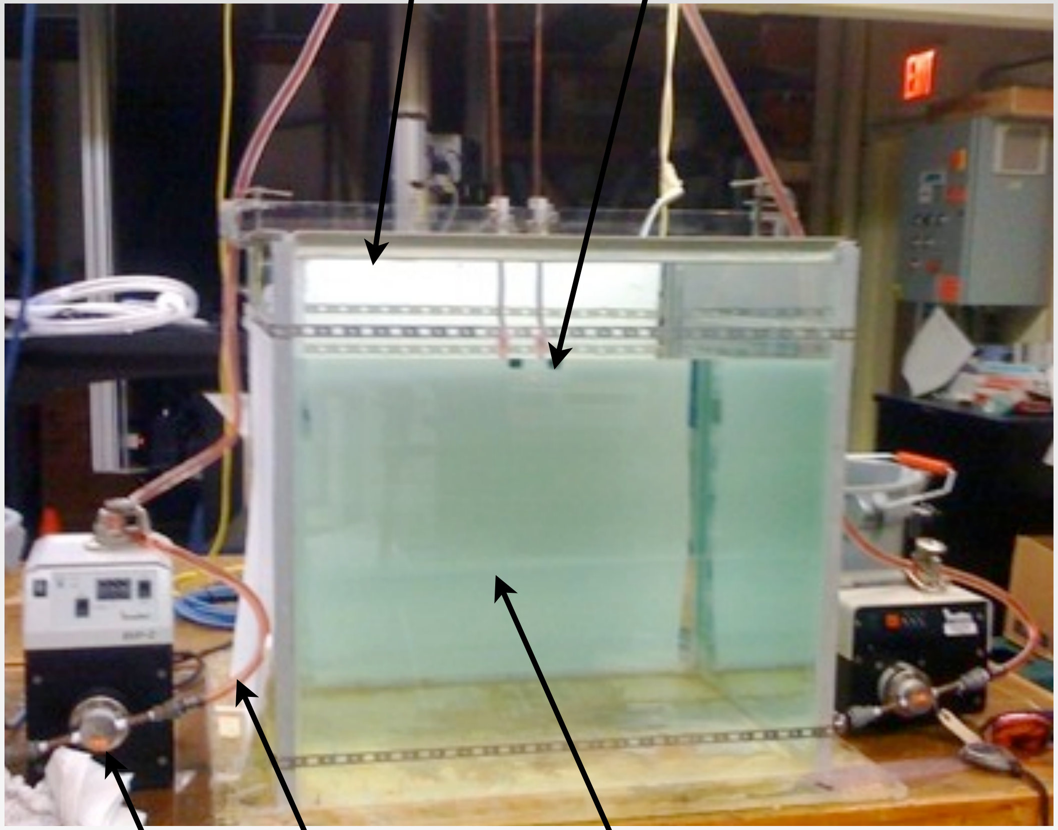


- The theory over estimated the laboratory results but was qualitatively correct.

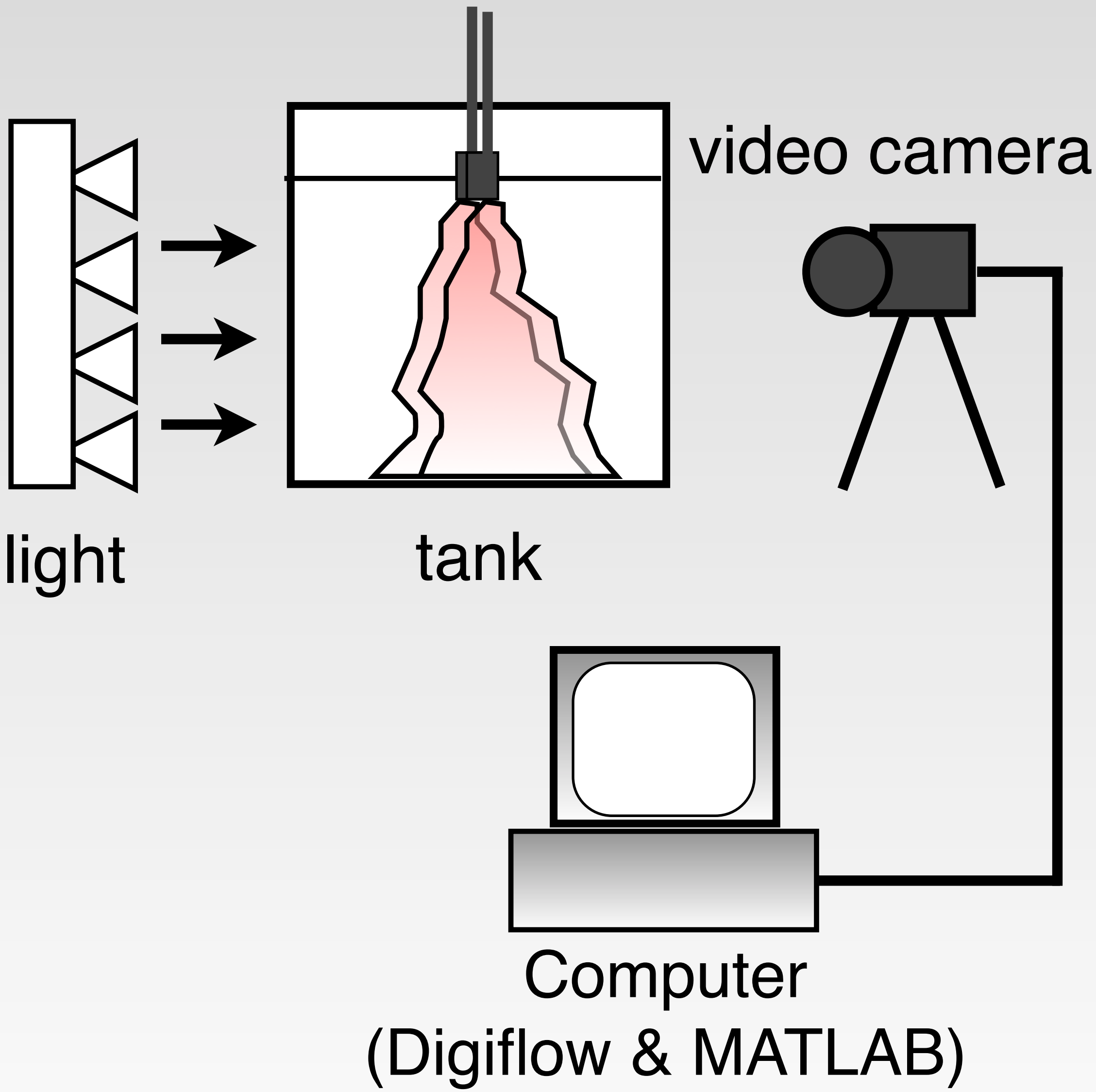
Two plumes experiment set up

- Tank cross section 60 x 60 cm^2
- Water depth 45 cm
- Fresh water (1g/cm^3) for ambient fluid
- Sea water (~1.25 g/cm^3) for plume colored by dye
- Flow rate = 1.7 cm^3/s ⇒

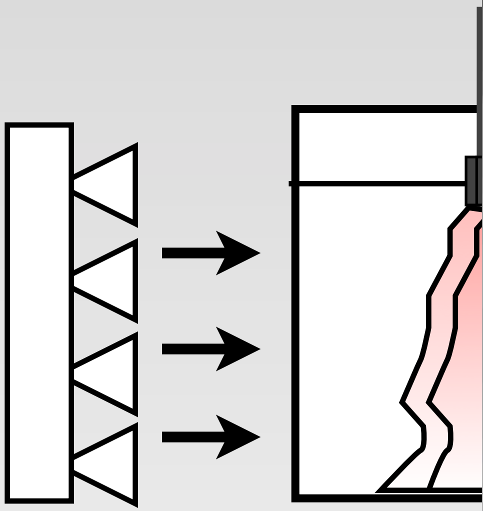
  buoyancy flux = 41 cm^4/s^3
- Cooper plume nozzle to produce a turbulent plume source



Dye attenuation technique



Dye que



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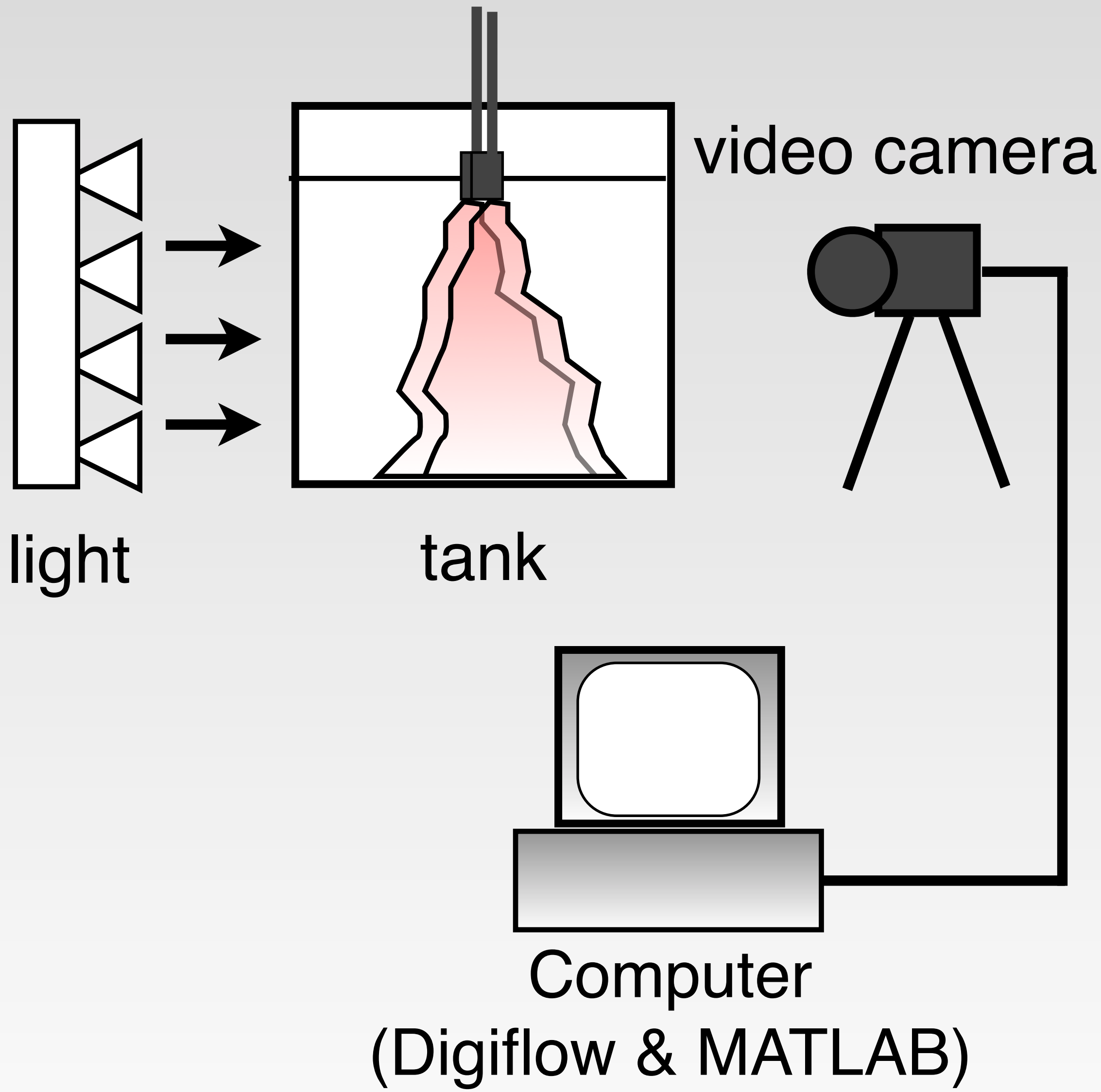
Dye attenuation technique



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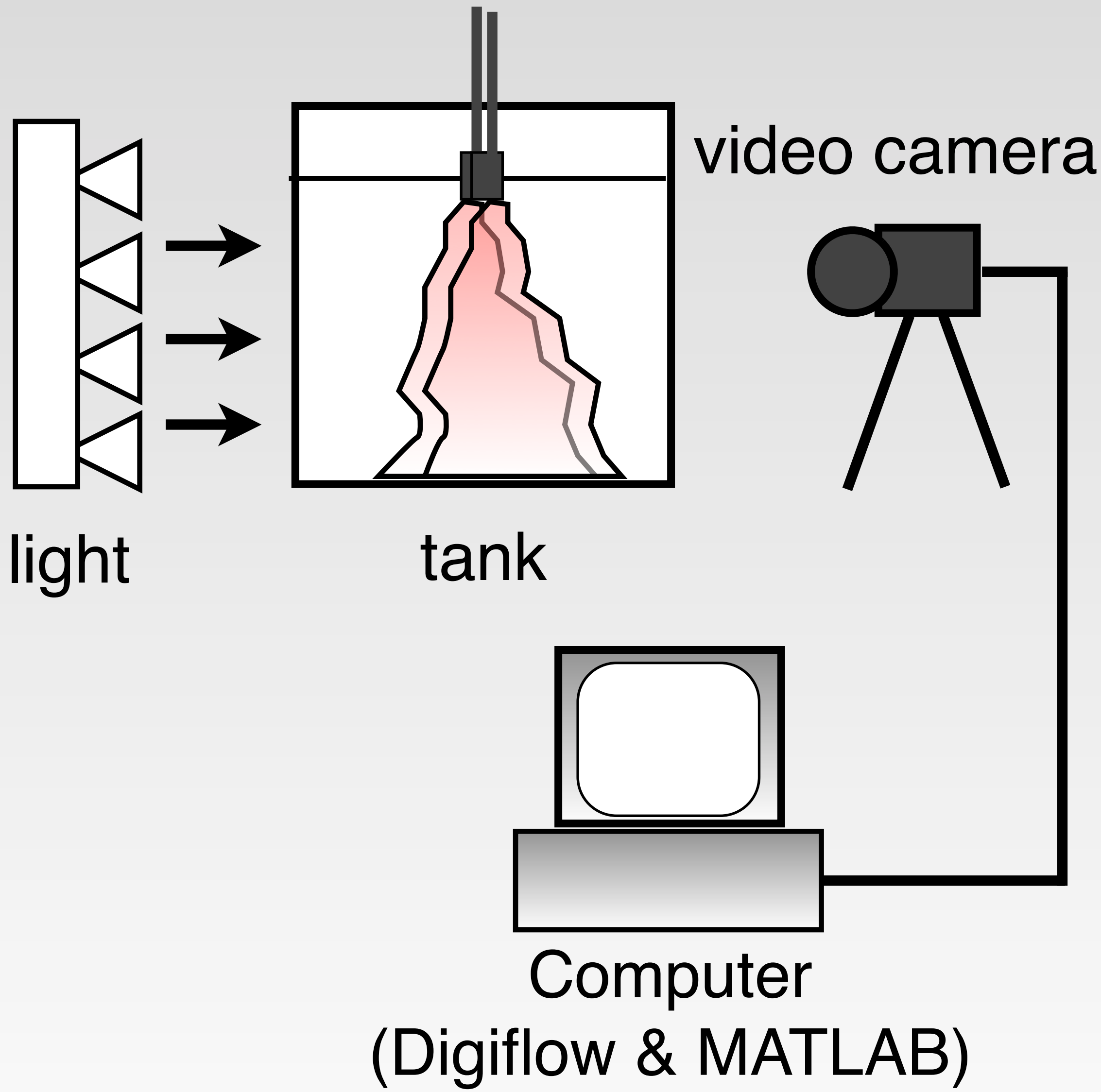
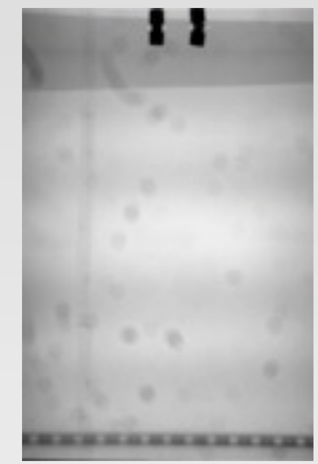
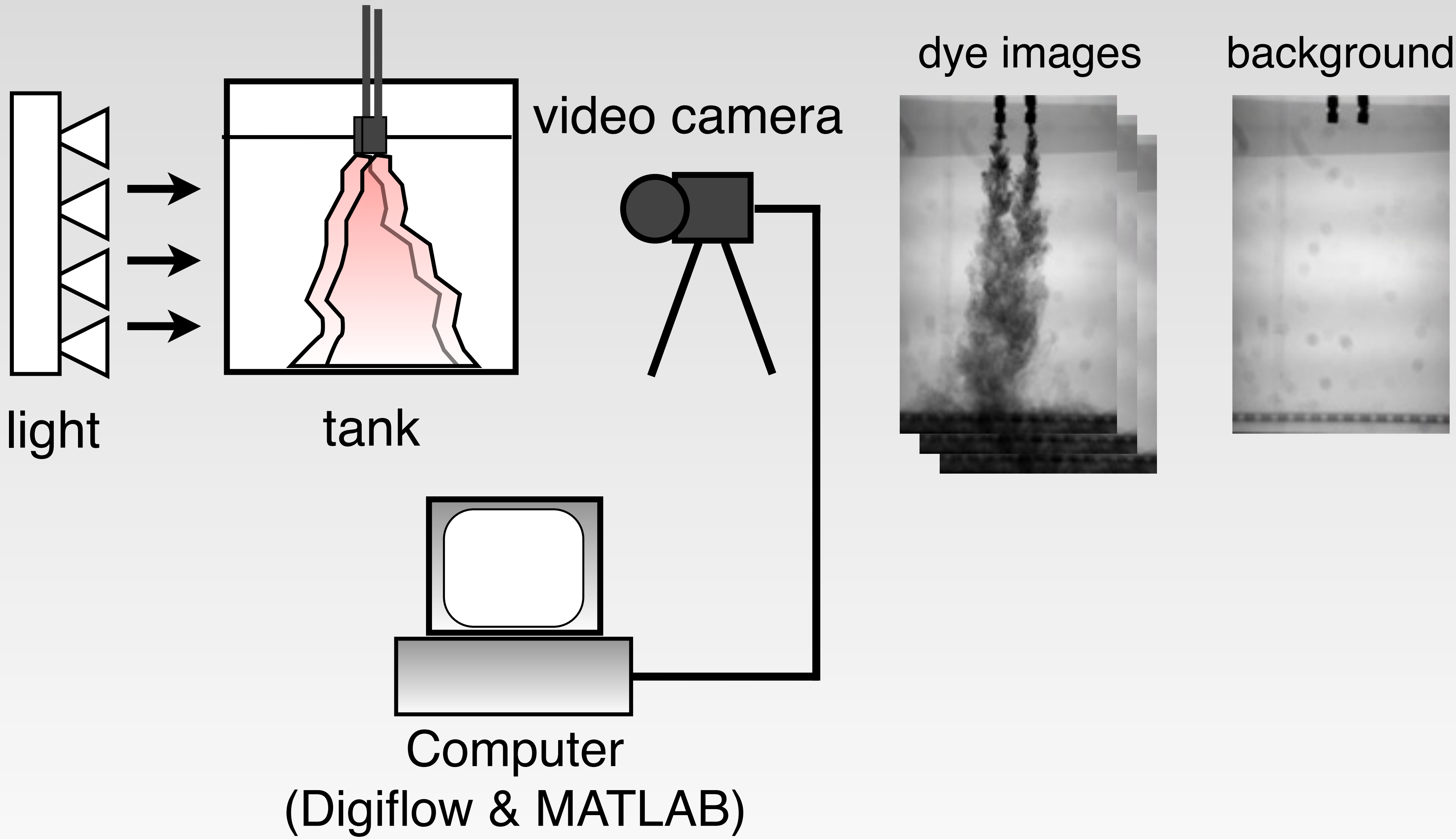


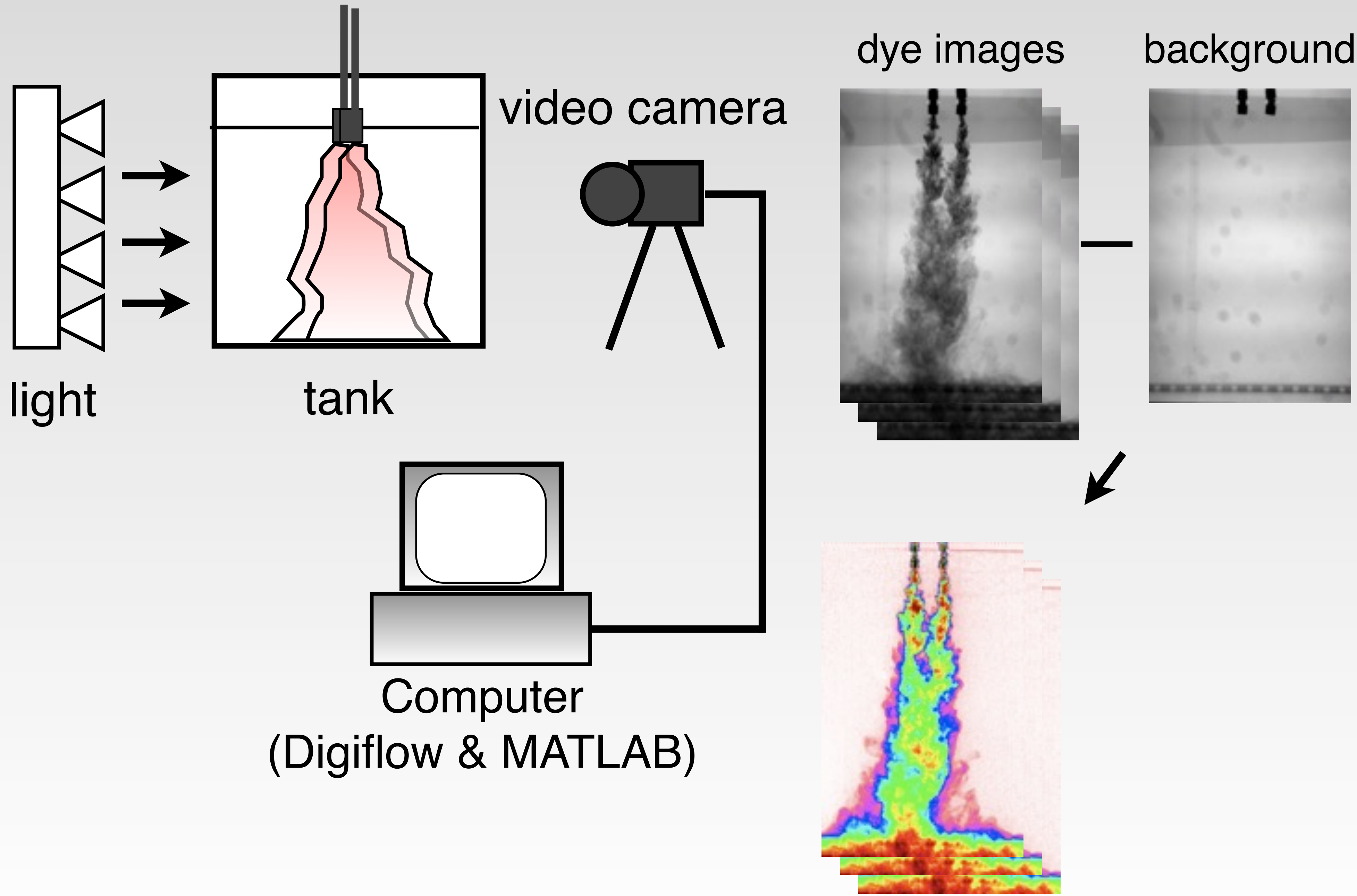
background



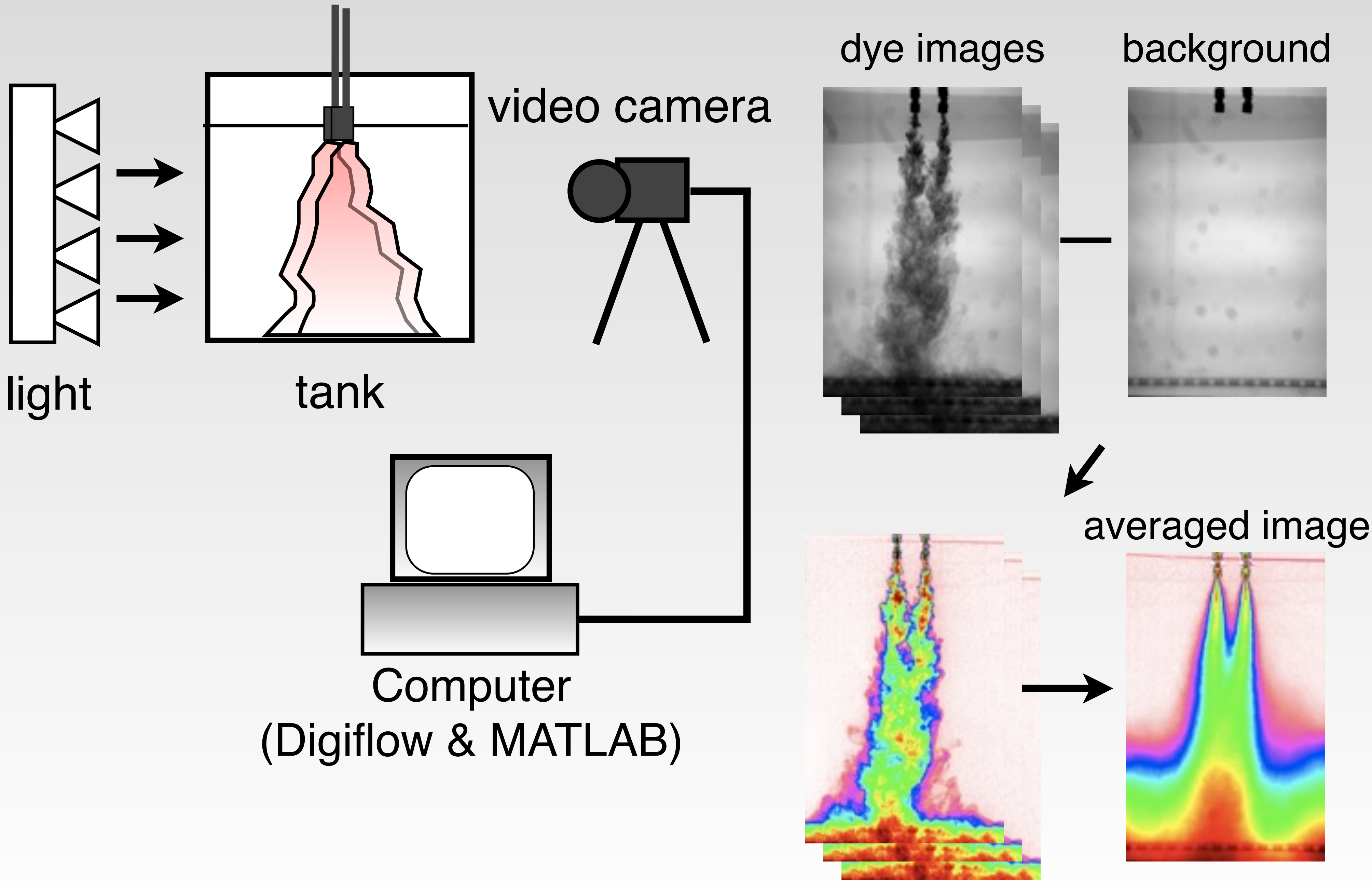
Dye attenuation technique



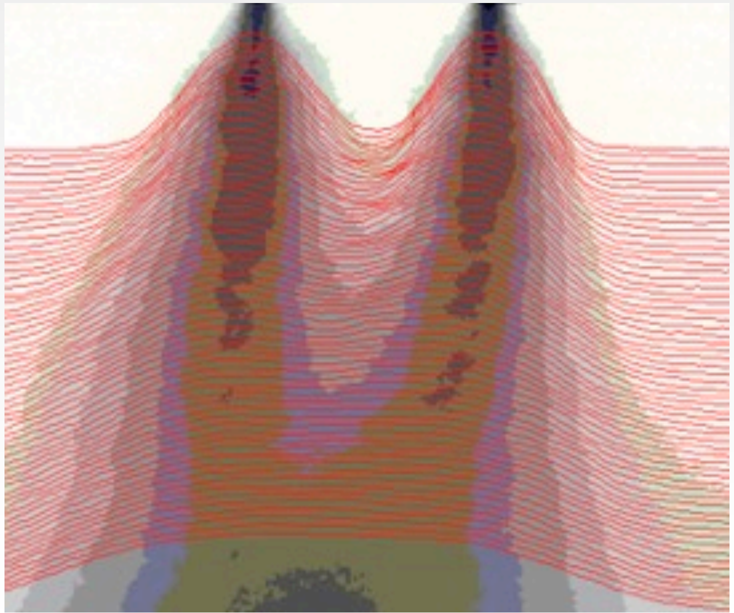
Dye attenuation technique



Dye attenuation technique

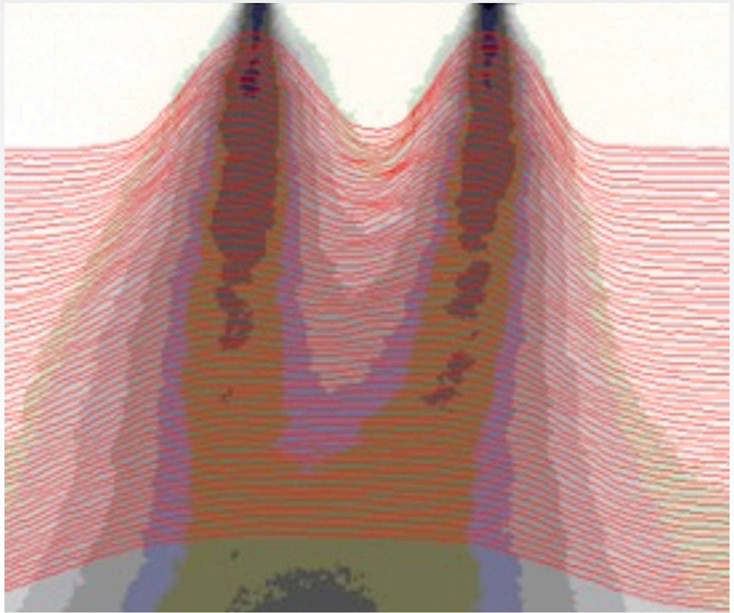


Algorithm

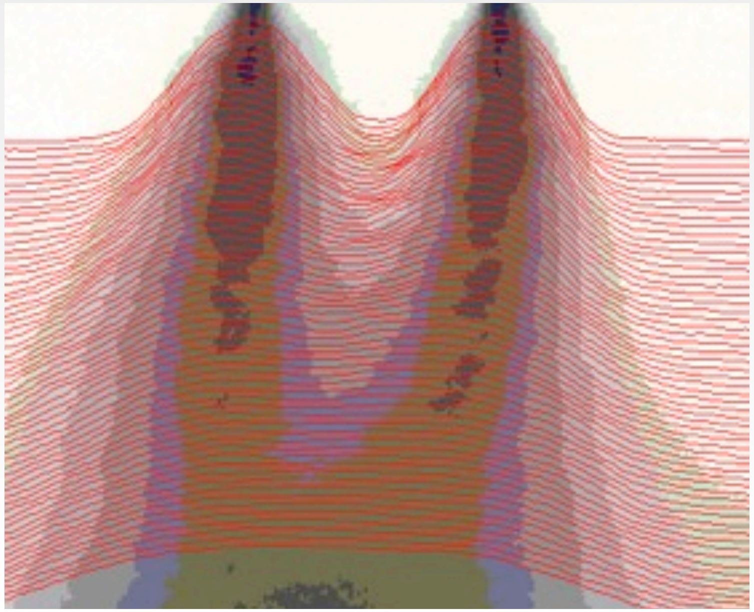


Algorithm

1. Smooth the image by box averaging every 7 pixels (if x_0 > 6 cm, 13 pixels) to remove noise.

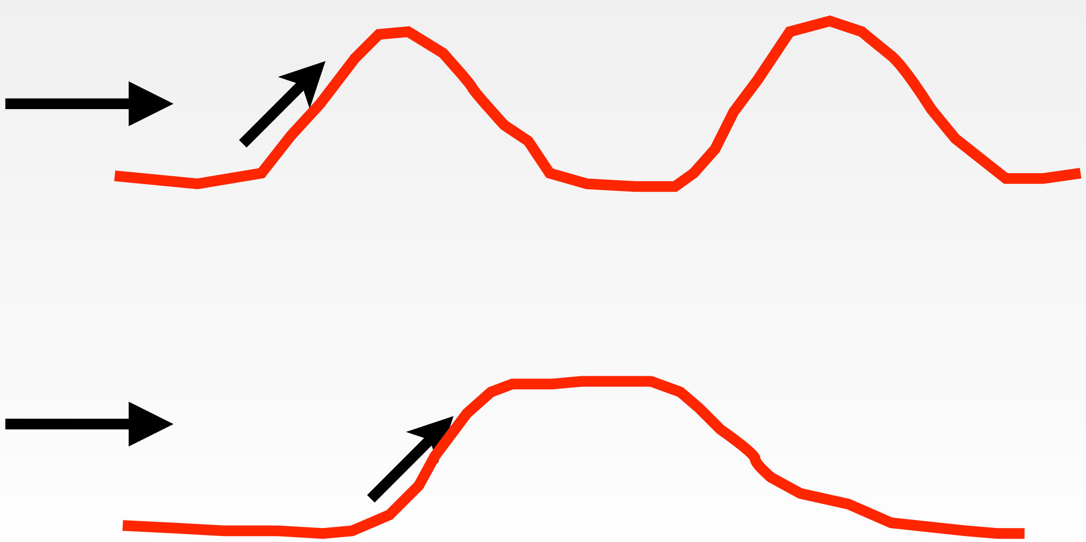


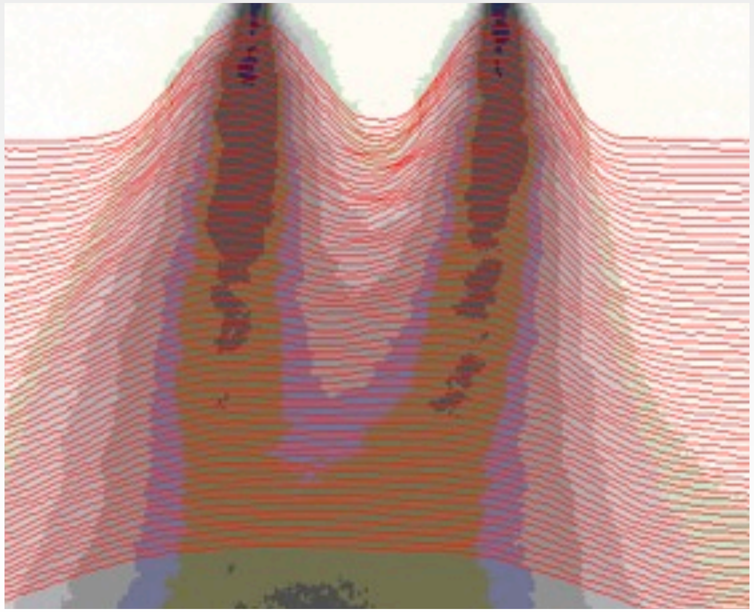
Smooth



Algorithm

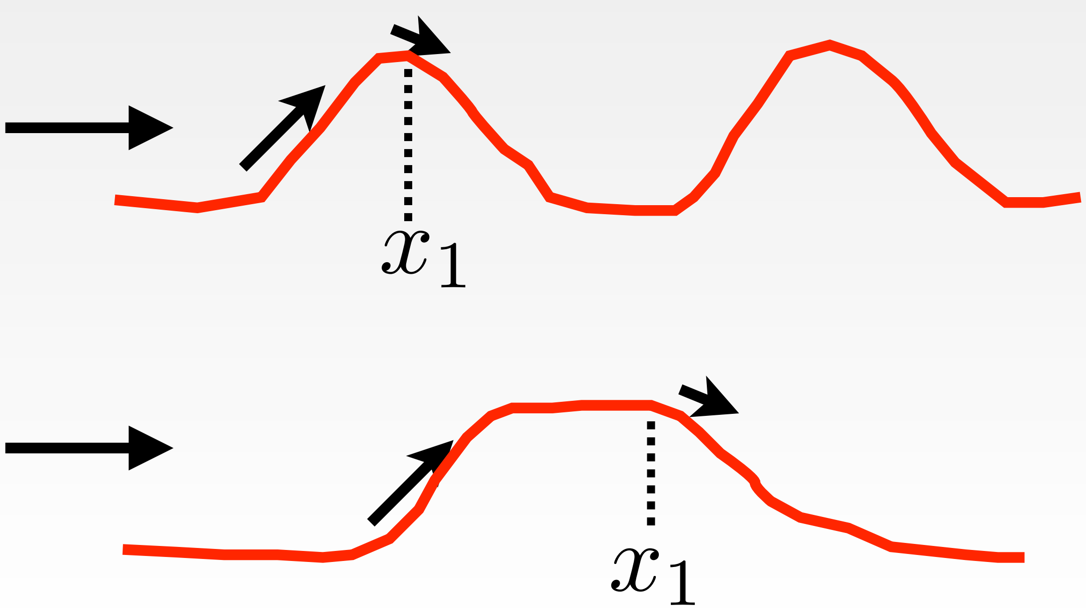
1. Smooth the image by box averaging every 7 pixels (if $x_0 > 6$ cm, 13 pixels) to remove noise.
2. Find a large slope ($dc/dx > \delta$; c: concentration) starting from the left.

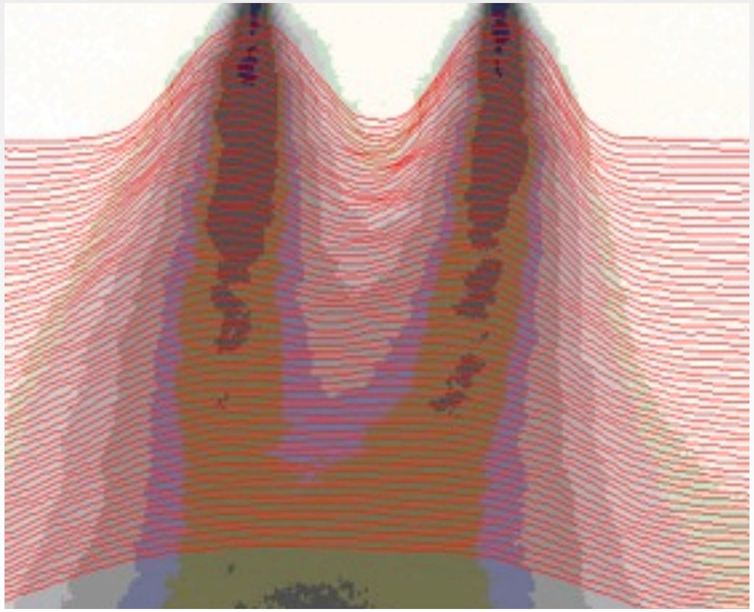




Algorithm

1. Smooth the image by box averaging every 7 pixels (if $x_0 > 6$ cm, 13 pixels) to remove noise.
2. Find a large slope ($dc/dx > \delta$; c: concentration) starting from the left.
3. From this point, find the location where the slope is negative ($dc/dx < 0$), and define this point as x_1.





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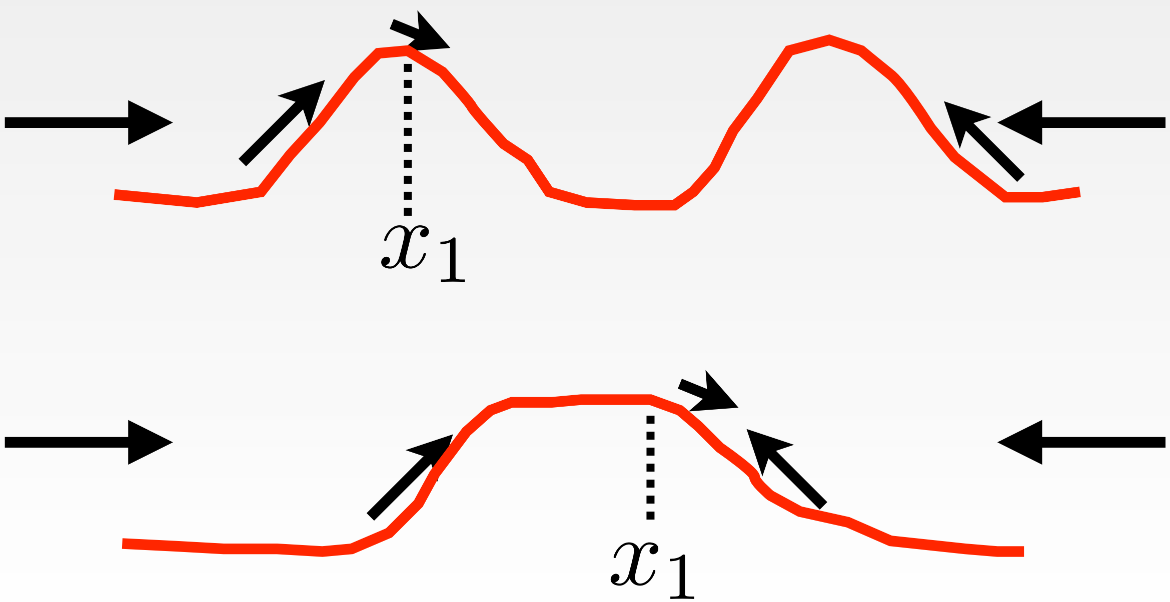

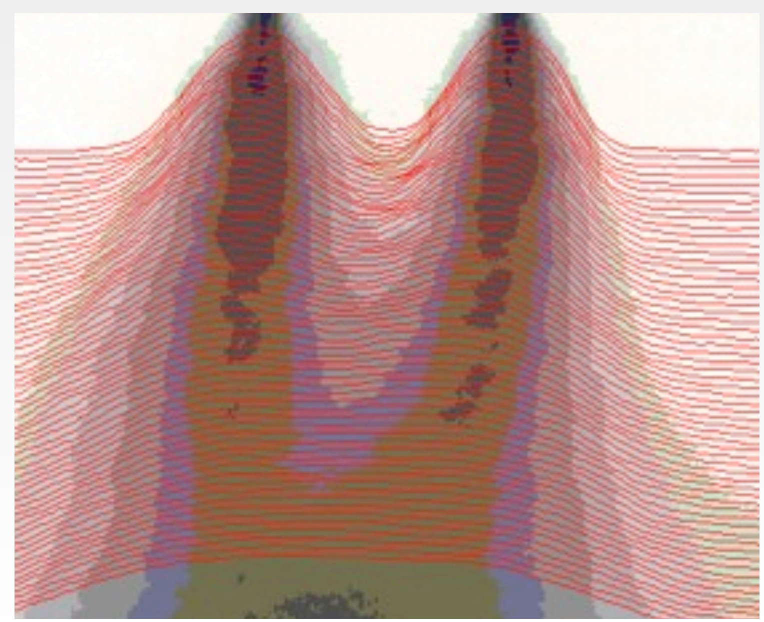

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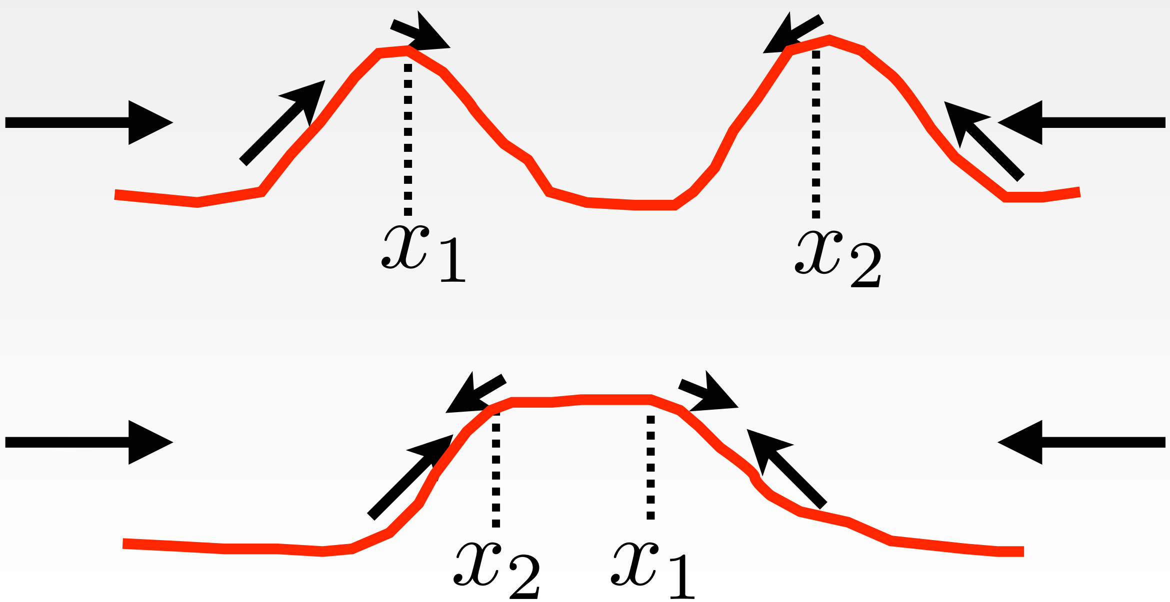

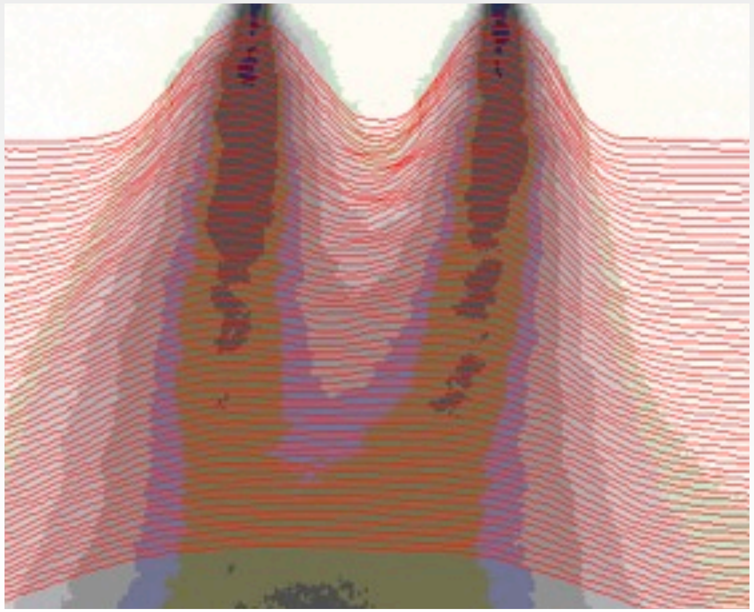

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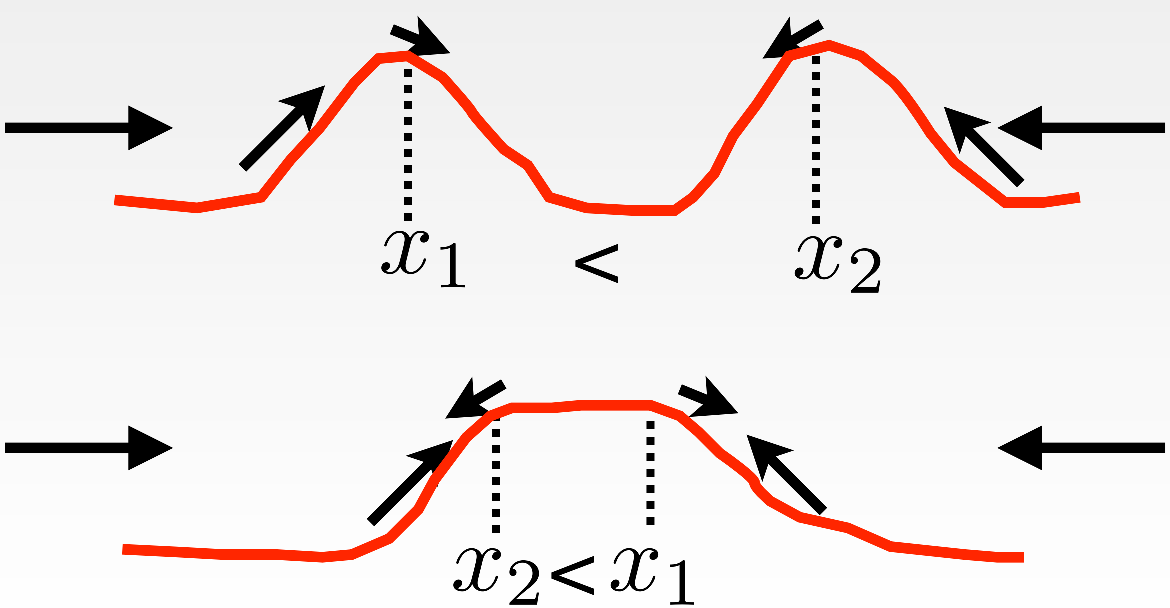
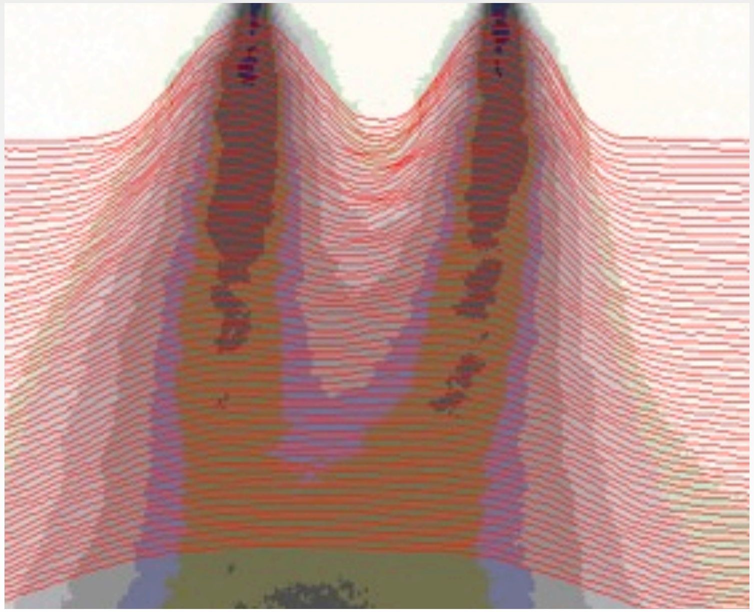
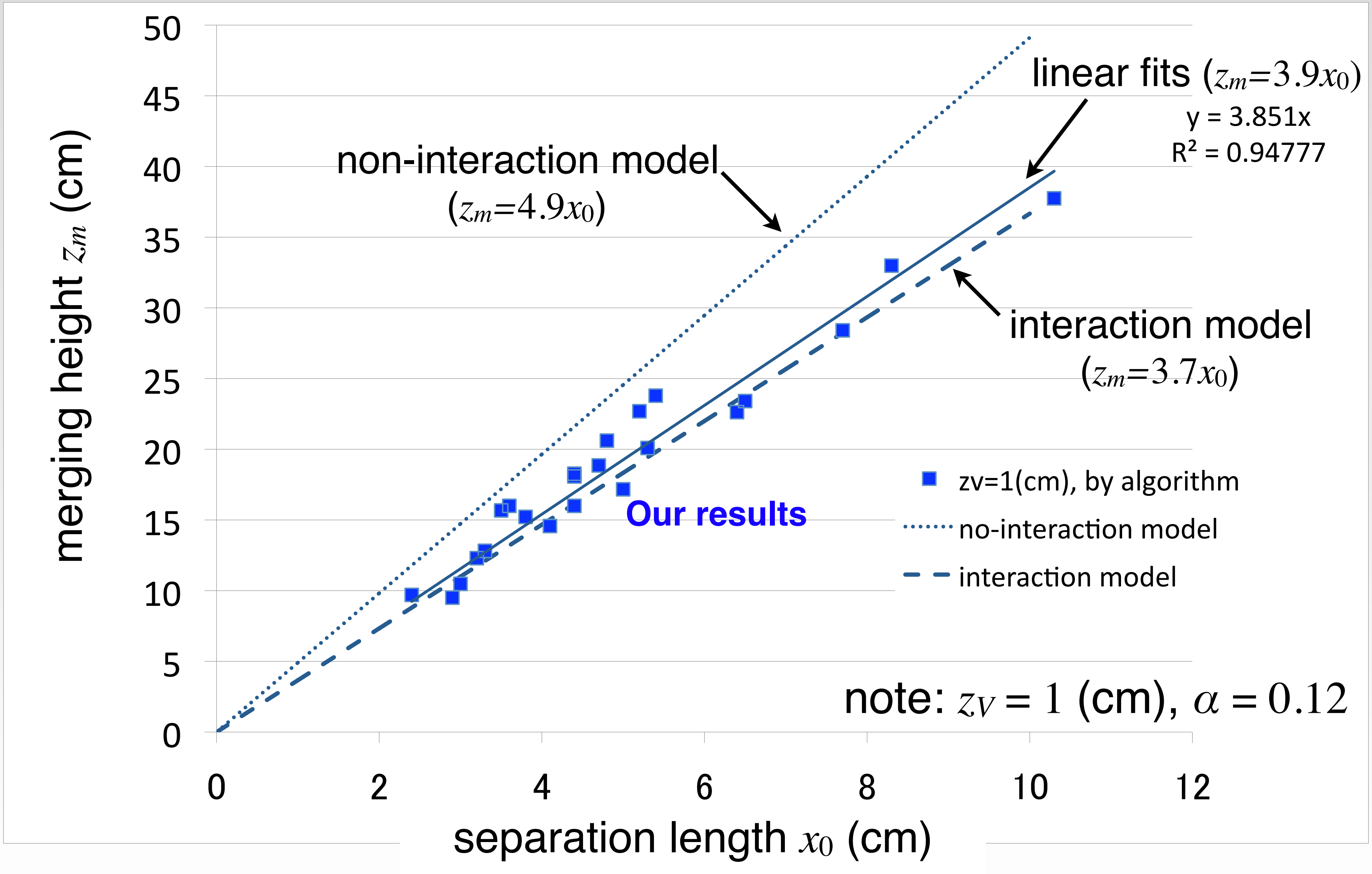
4. Find a large slope ($dc/dx < -\delta$) starting from the right.
5. From this point, find the location where the slope is positive ($dc/dx > 0$), and define this point as x_2.
6. $x_1 > x_2$ means plumes are merged, $x_1 < x_2$ means plumes are not merged.





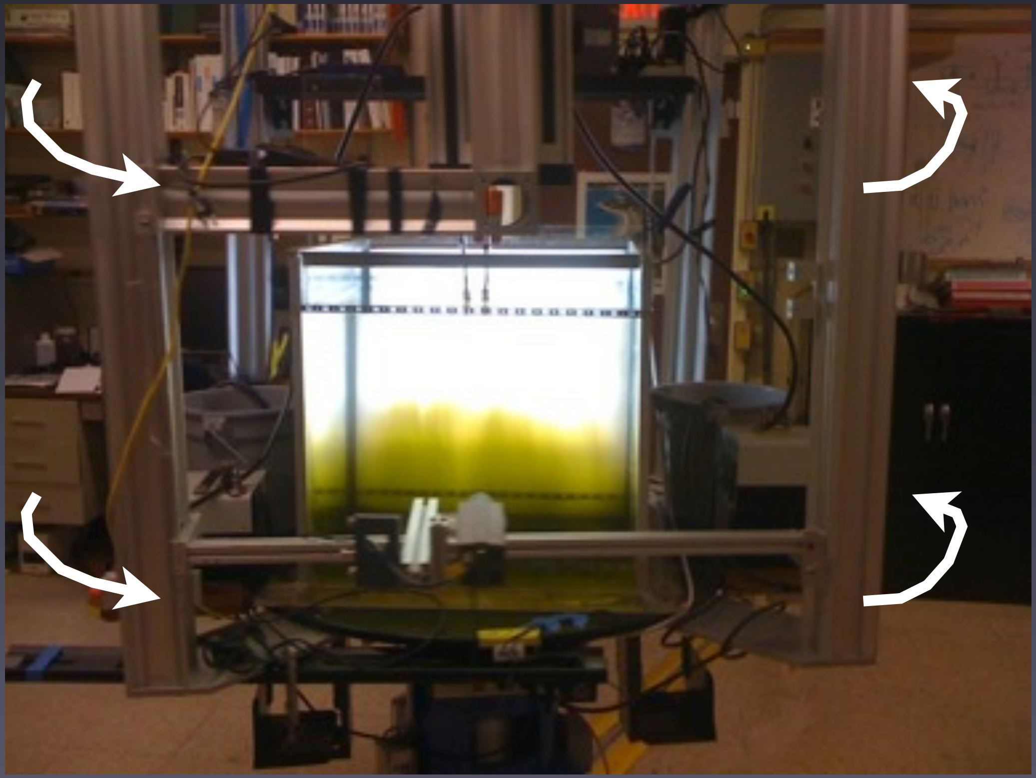
Results of two plumes experiments without rotation



Summary of non-rotating experiments

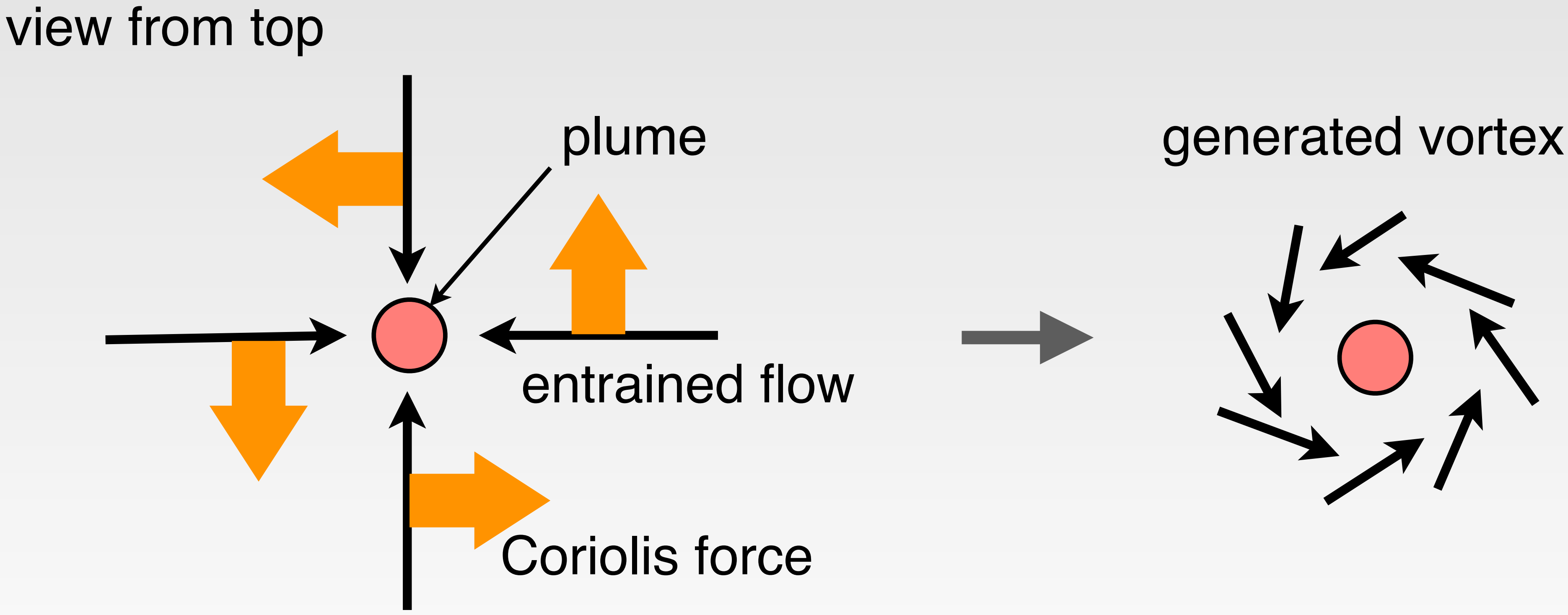
- I carried out the coalescing two plumes experiment for $\alpha = 0.12$.
- I measured the merging height using the algorithm.
- My experimental results agree with the theoretical prediction.
- This is highly dependent on the value of α.

Two plumes experiments with rotation



Effect of rotation

- In a rotating frame there is the Coriolis effect
- A vortex will be generated by the Coriolis force induced by the entrained flow.



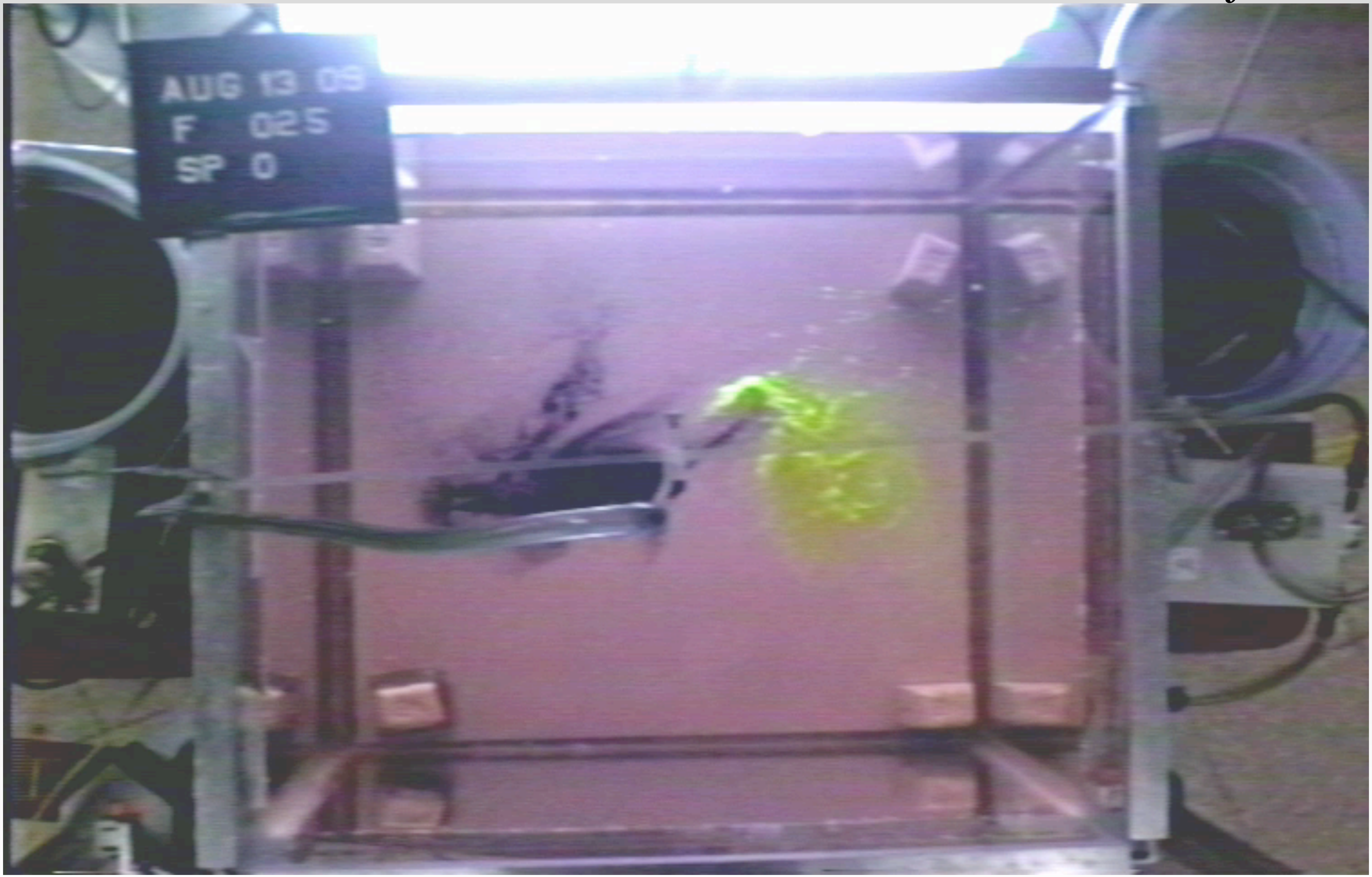
- The flow field tends to be barotoropic, because of the absence of stratification.

Single plume with rotation f = 0.25 s^{-1}

$(f = 2\Omega)$

Single plume with rotation $f = 0.25\ \mathrm{s}^{-1}$

$(f = 2\Omega)$



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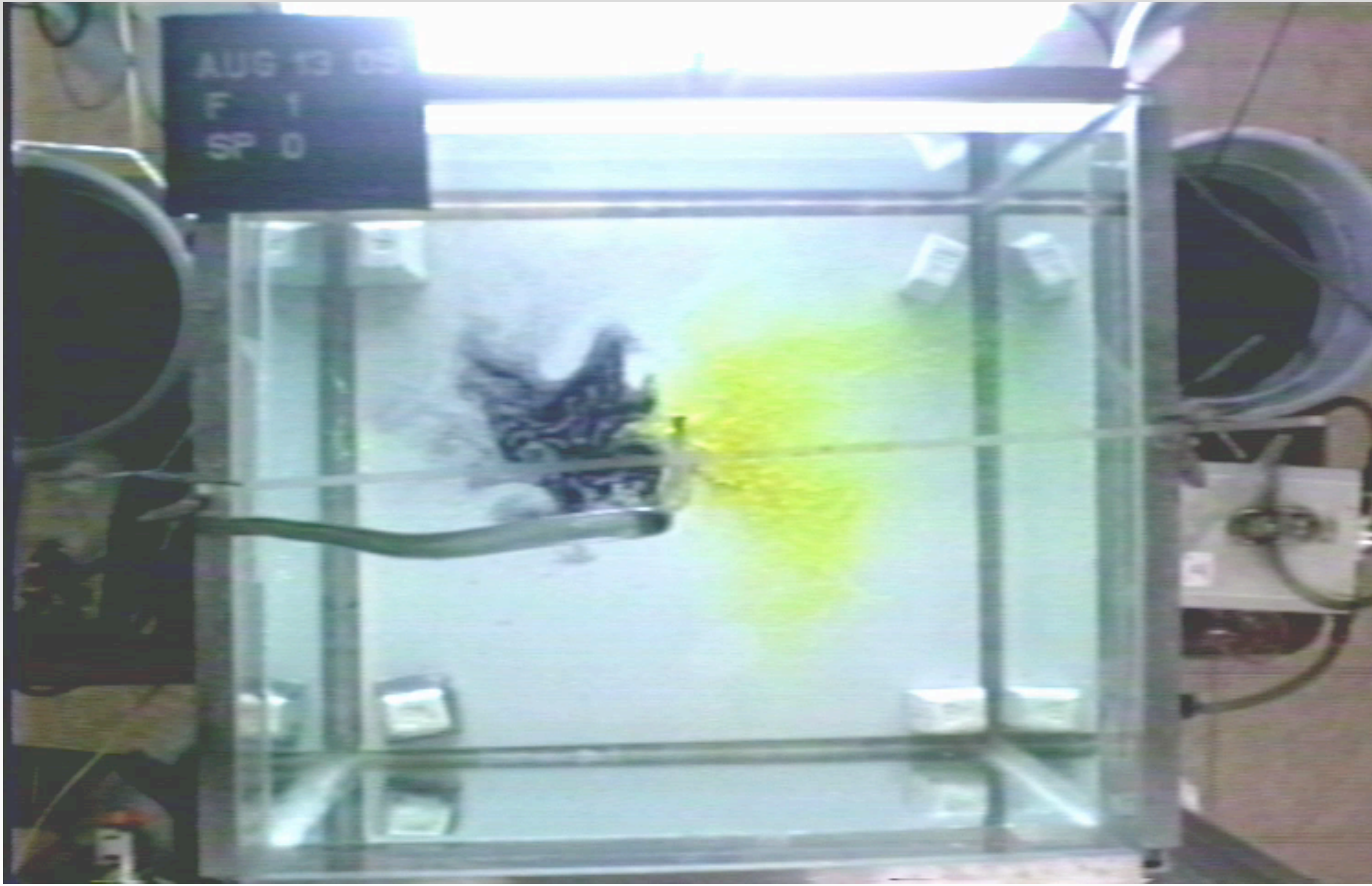

experimental set up

- rotation : $f = 0.05, 0.1, 0.25, 0.5, 0.75, 1.0$ (s^{-1})
  ($f = 2\Omega$)
- separation : $x_0 = 3, 5, 8, 10$ cm
- the other settings are the same as the non-rotating experiments.

Two plumes experiment with rotation

f = 0.25 s^{-1}, x_0 = 5 cm

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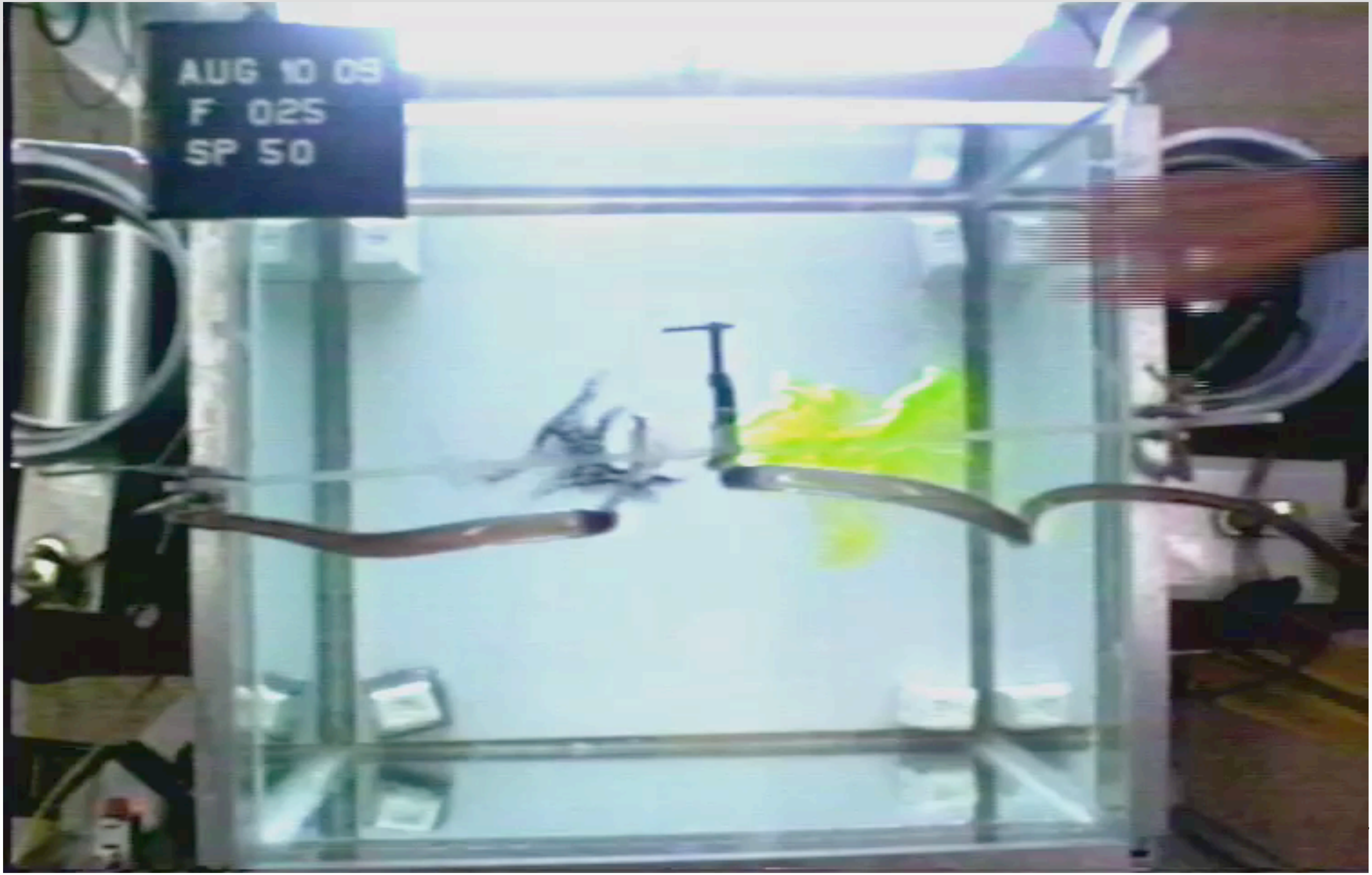

Two plumes experiment with rotation

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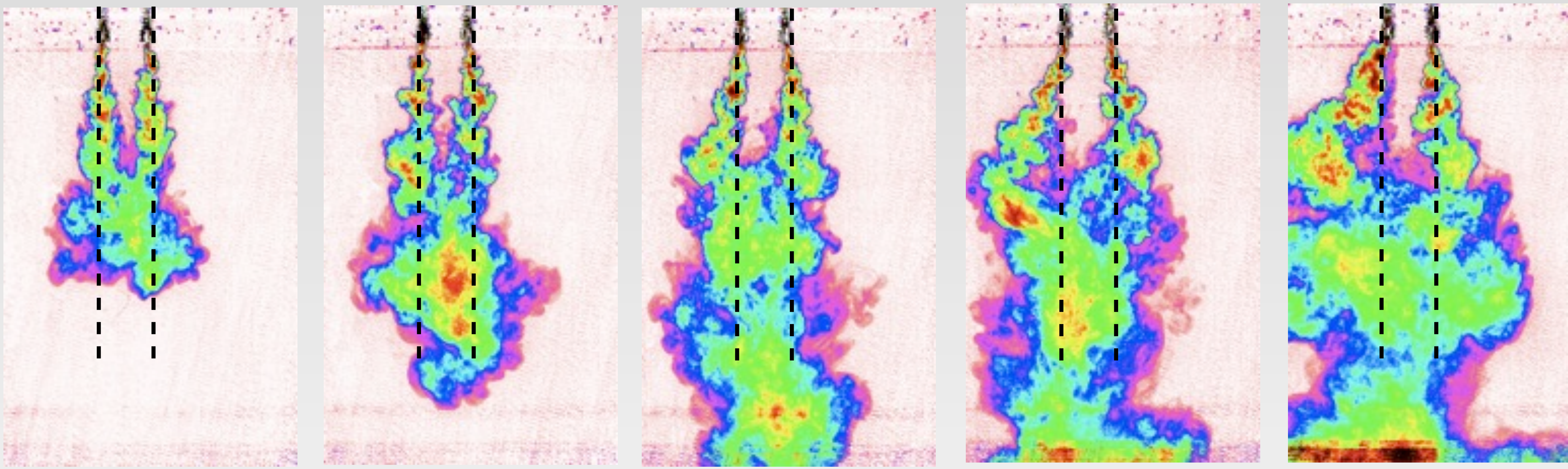

$t = 0.4T_f$ $0.6T_f$ $0.8T_f$ $1.0T_f$ $1.2T_f$

($T_f = 2\pi/f$: inertial period)

Two plumes experiment with rotation
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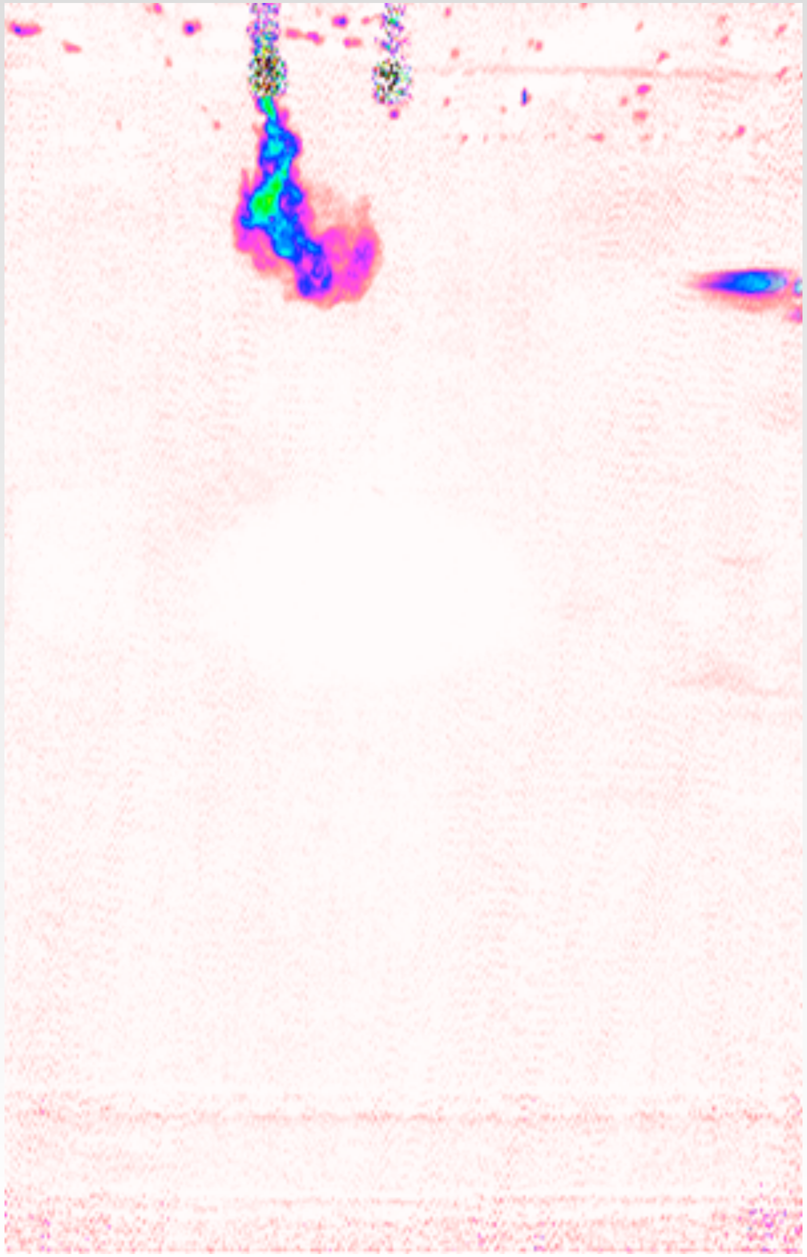

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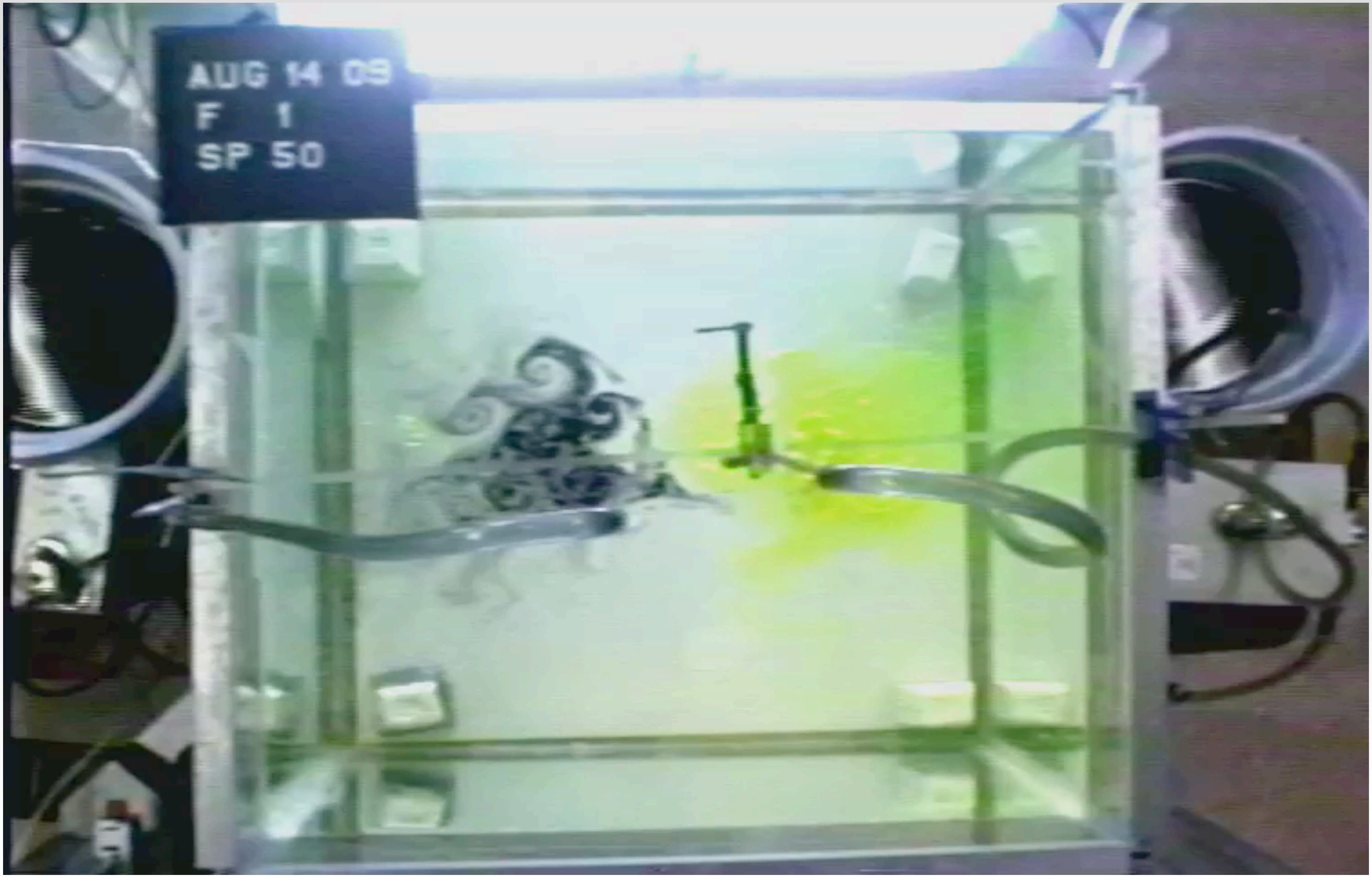

Two plumes experiment with rotation

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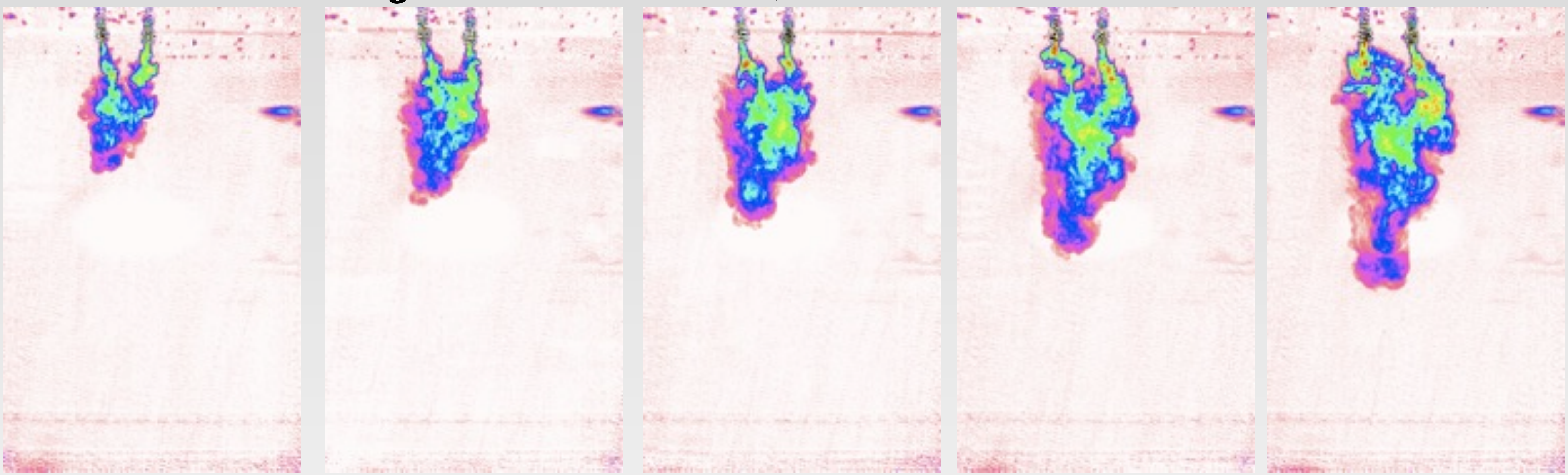
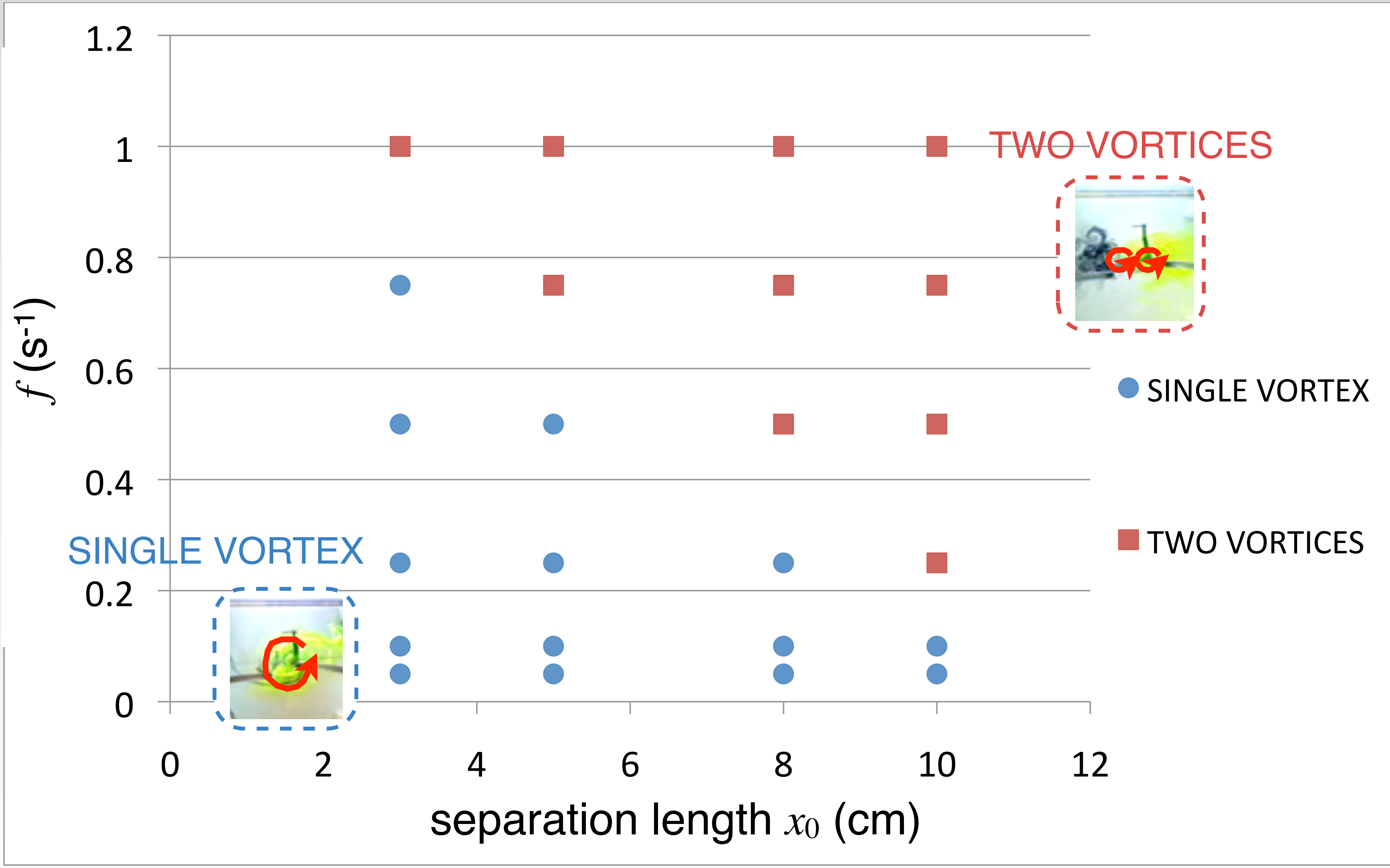


$t = 0.4T_f$ $0.6T_f$ $0.8T_f$ $1.0T_f$ $1.2T_f$

Results of vortices



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- Effect of rotation becomes important for $t \sim T_f$, where $T_f = 2\pi/f$ is the inertial period.

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- When f is small, one vortex is generated at the center of the two plumes.
- When f is large, two vortices are generated one from each plume, and the vortices shed from the sources.

Study of development of point plume in rotating frame

- Fernando, Chen, and Ayotte (1998; FCA) carried out a laboratory study on the development of a single turbulent plume in a rotating frame.
- Their results show that the effect of rotation becomes important for

$$t \sim 2.4/\Omega \sim 0.75T_f$$

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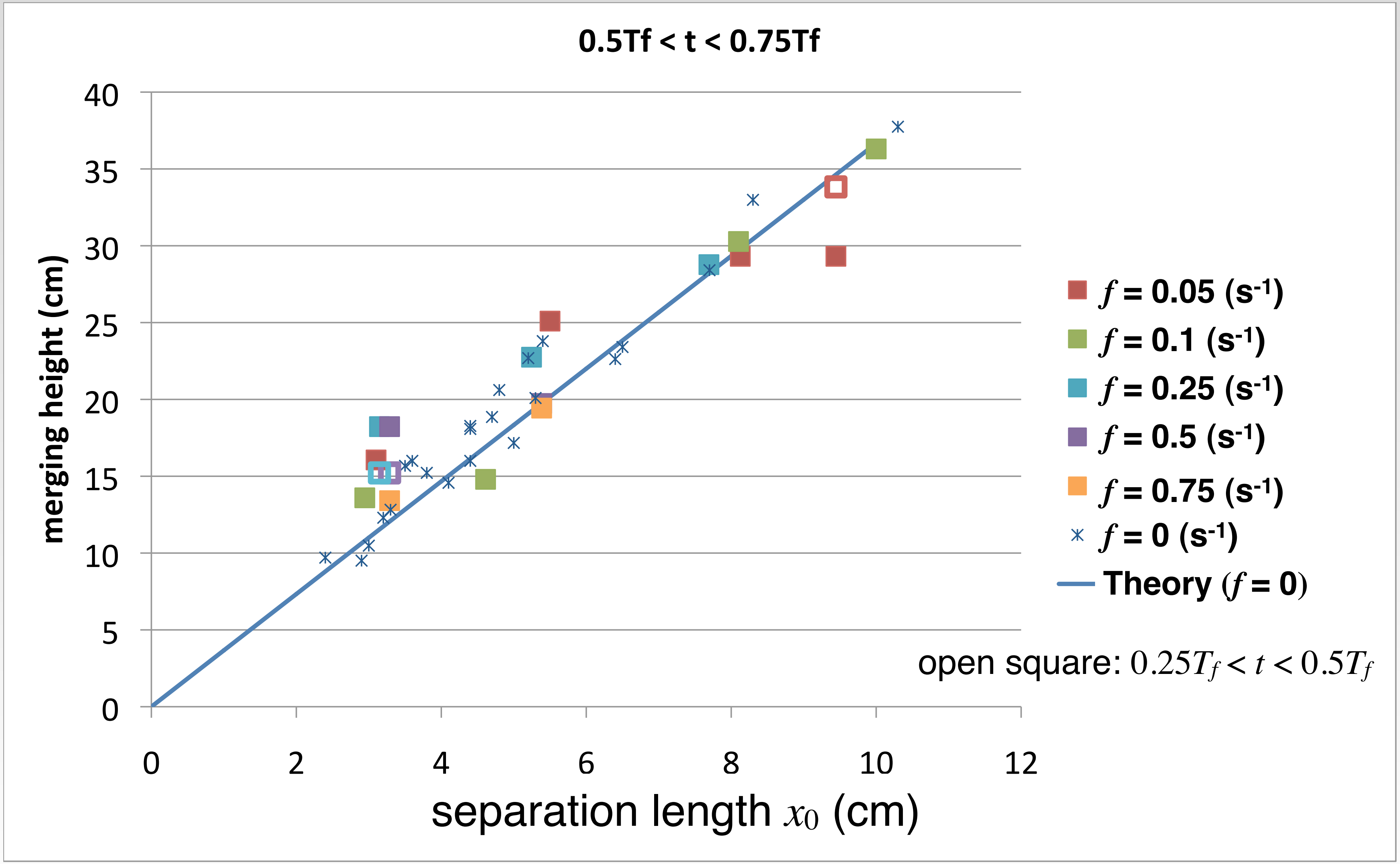
How about our results?

Merging height at $0.5T_f < t < 0.75T_f$



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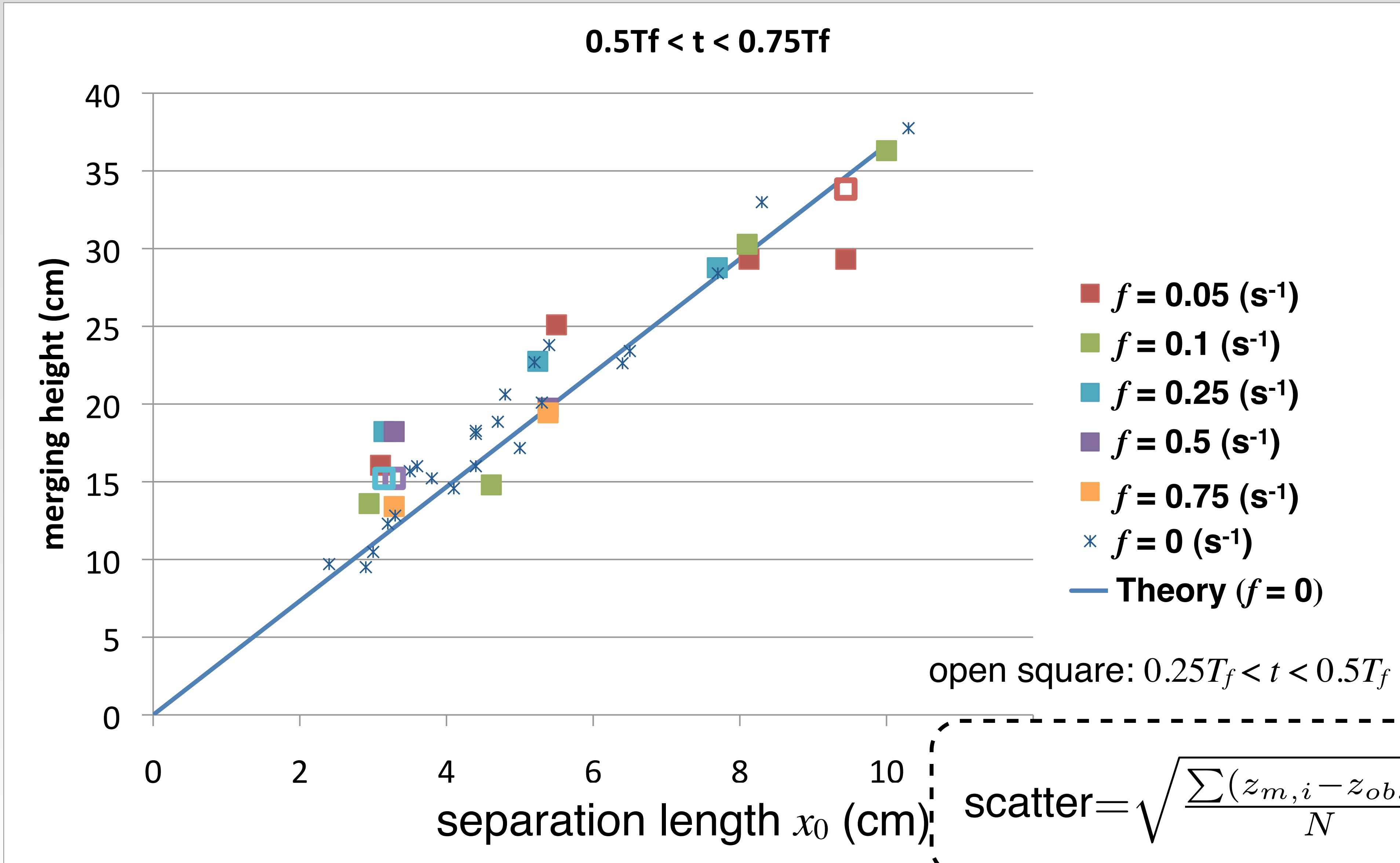
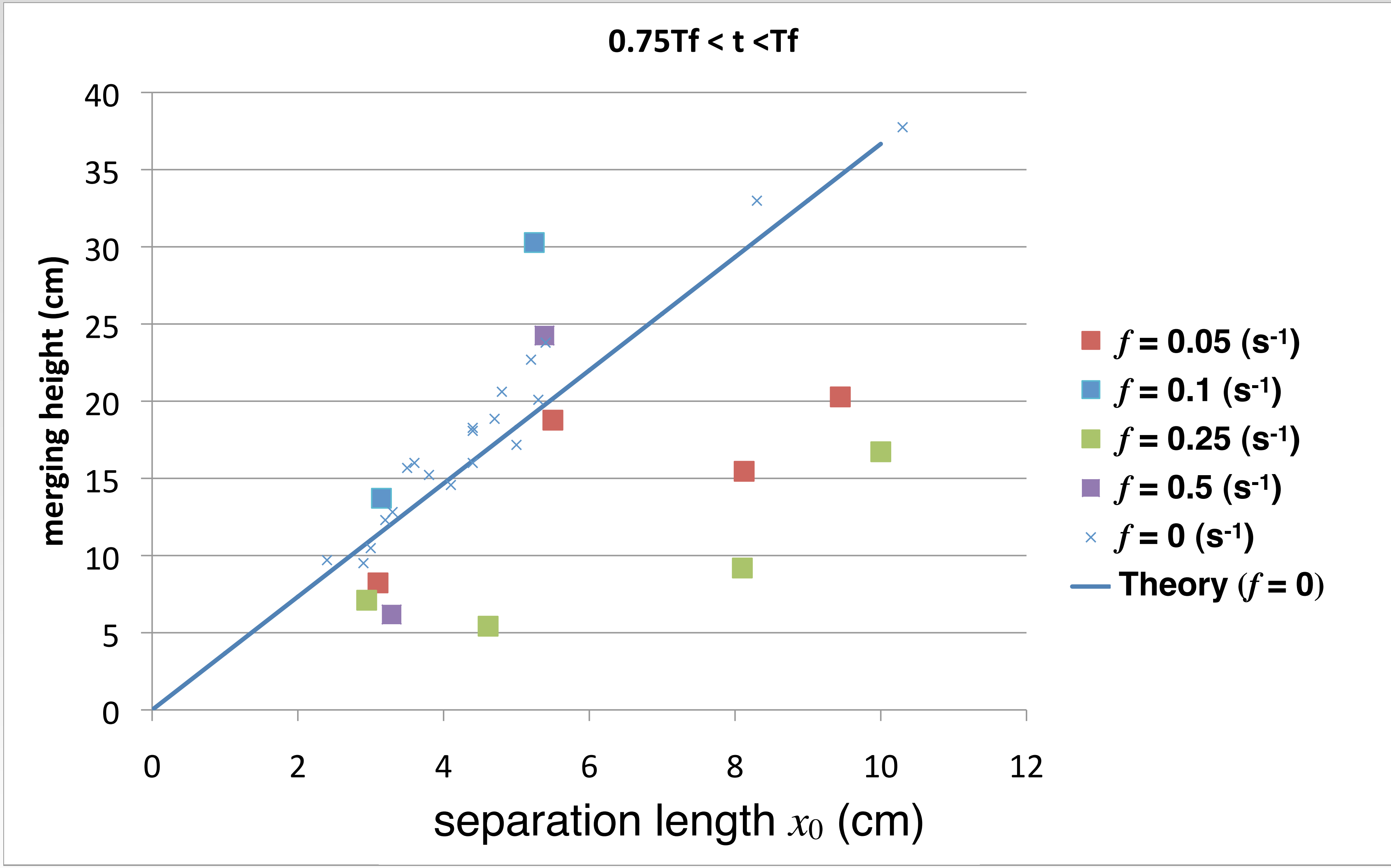


$$\text{scatter} = \sqrt{\frac{\sum (z_{m,i} - z_{obs,i})}{N}}$$

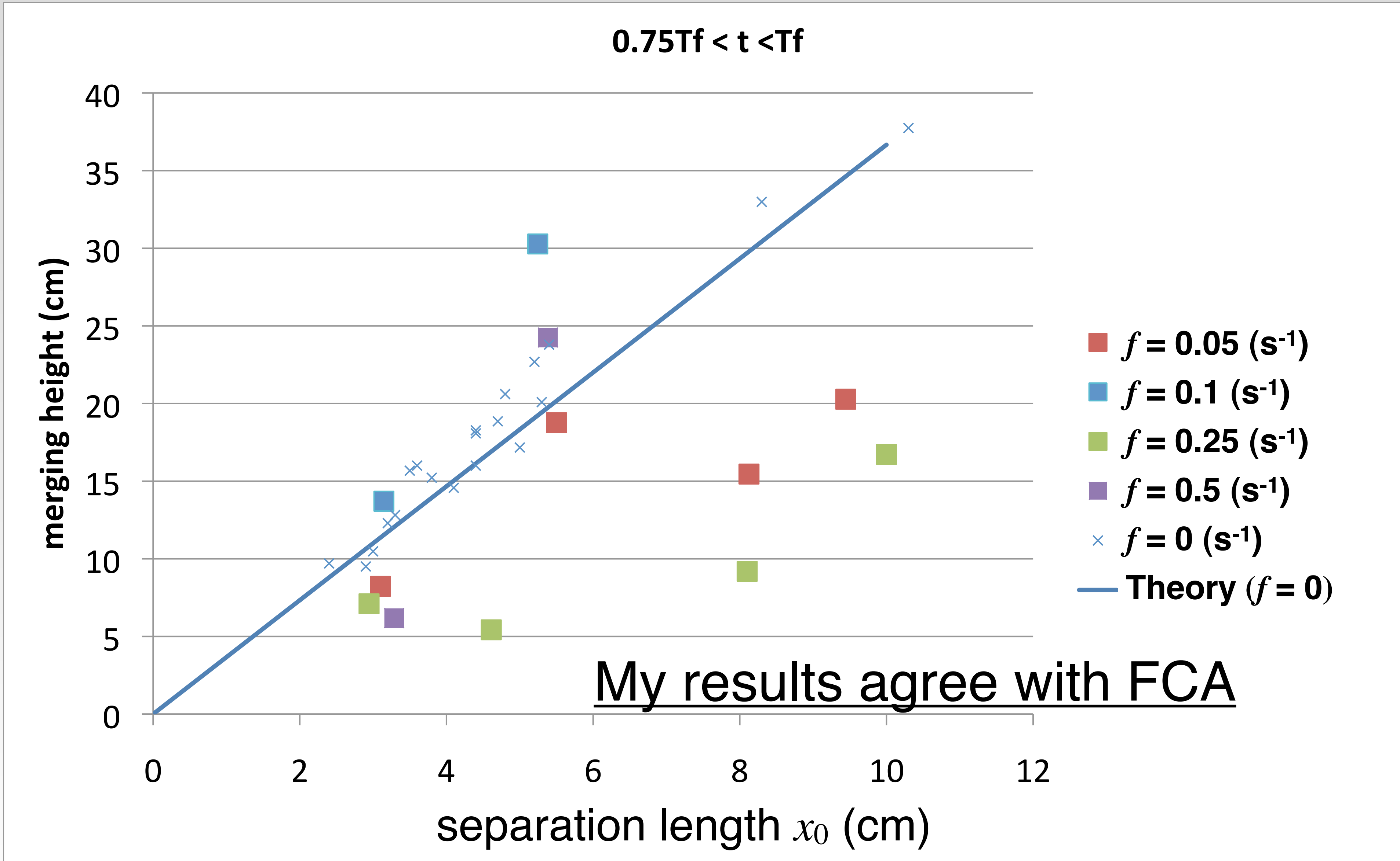
scatter: $f = 0 \rightarrow 1.85$ cm, $f > 0 \rightarrow 2.89$ cm

Merging height at $0.75T_f < t < T_f$



scatter: $f = 0$ → 1.85 cm, $f > 0$ → 10.98 cm

Merging height at $0.75T_f < t < T_f$



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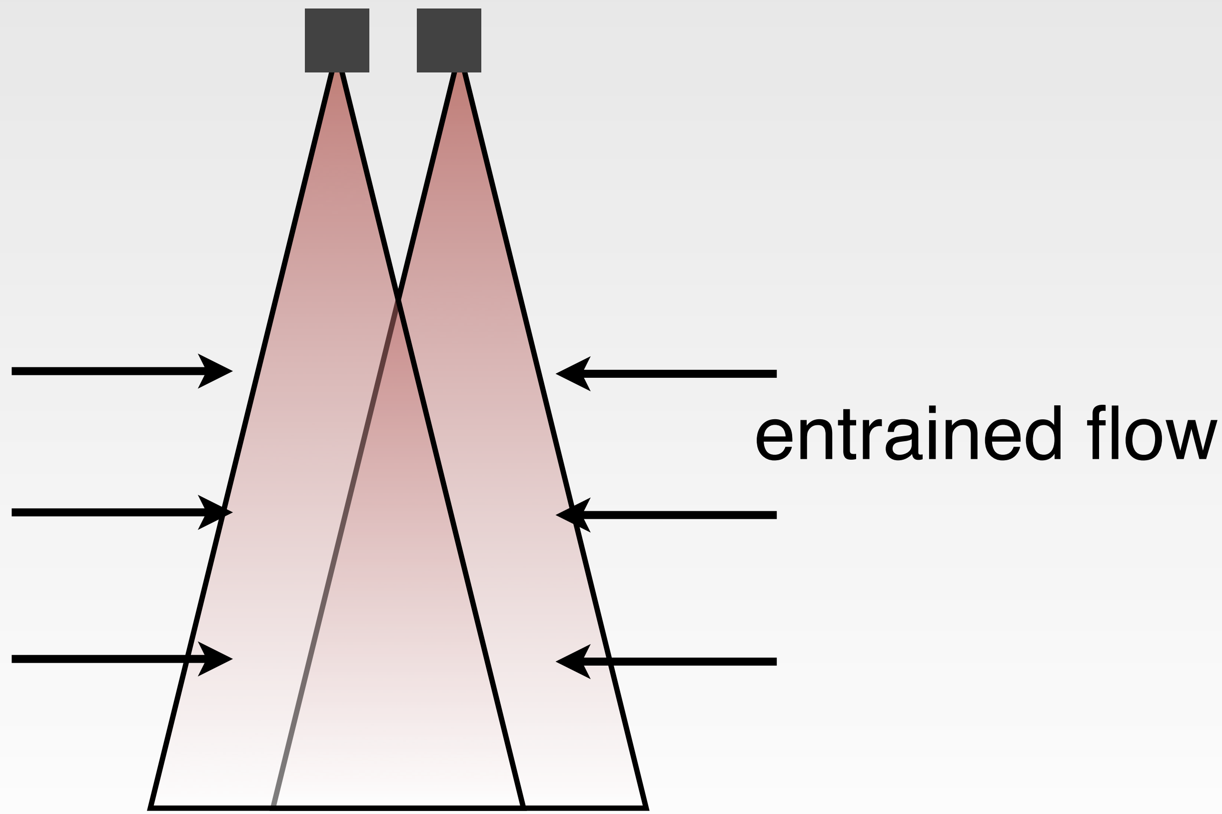
A vortex generated by merged plume

- It can be considered that the single vortex observed at the center of the two plums was generated **after** the two plumes merged by the **resulting single** plume.



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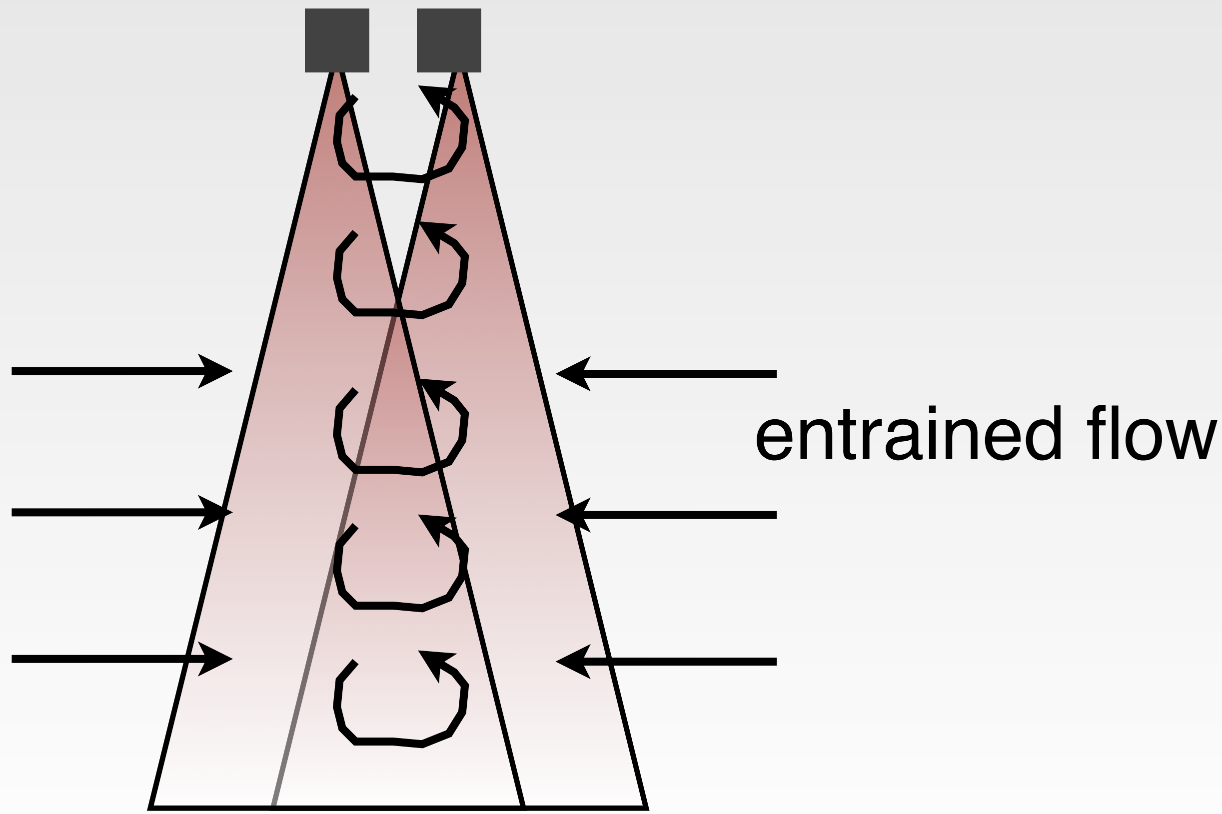
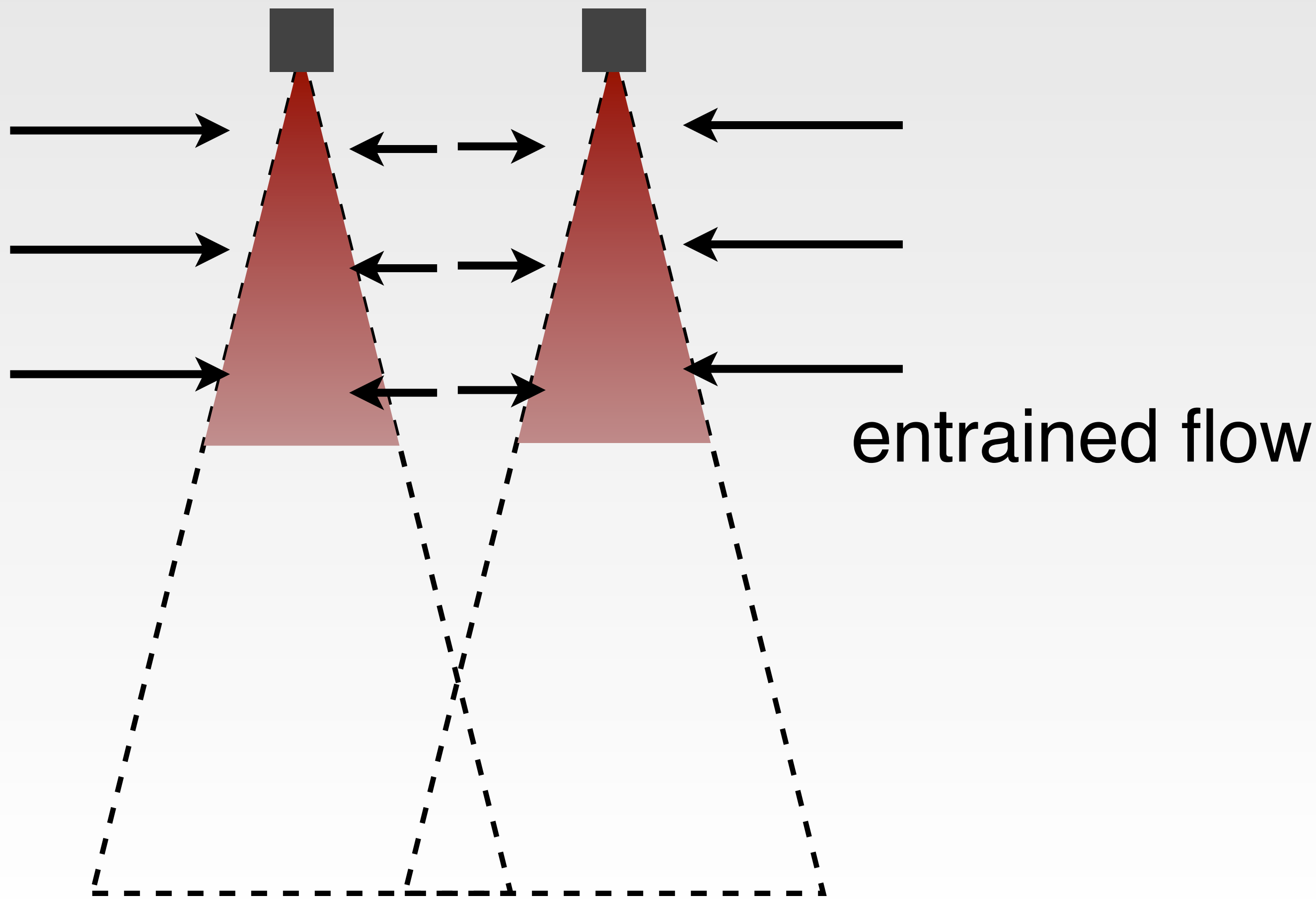


Vortices generated by individual plumes

- It can be considered that the two vortices observed below each sources were generated **before** the plumes merged by **each individual plume**.



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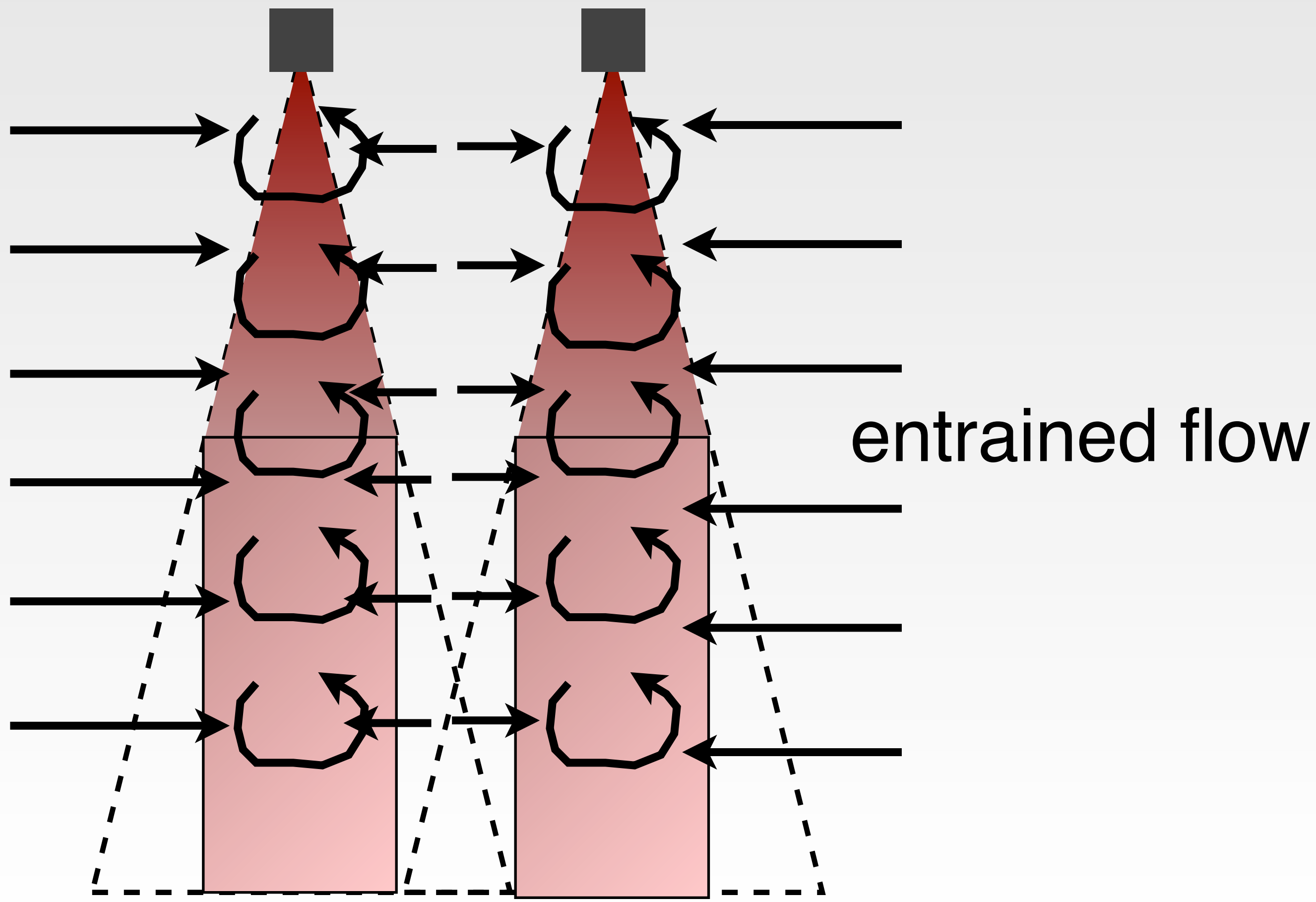

How does the plume descend?

- The vertical velocity w of the plume is predicted to be (Baines and Turner, 1969)

$$w = \frac{5}{6\alpha}\left(\frac{18\alpha F_0}{5\pi}\right)^{\frac{1}{3}} z^{-\frac{1}{3}}$$

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- so we can calculate the time scale to travel from the source ($z = 0$) to z,

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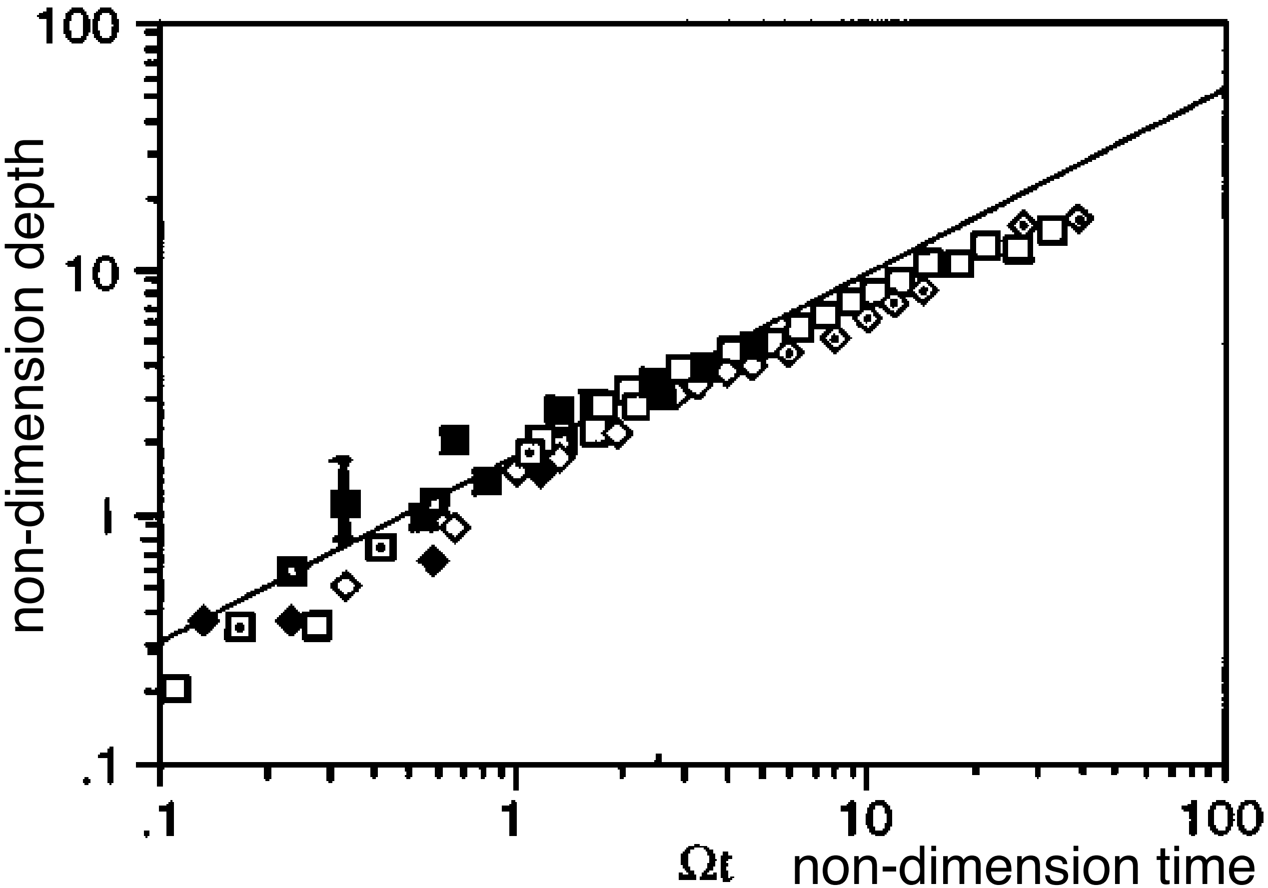
- **However, this theory is for steady state, not applicable to the plume's front.**

How does the plume's front descend?

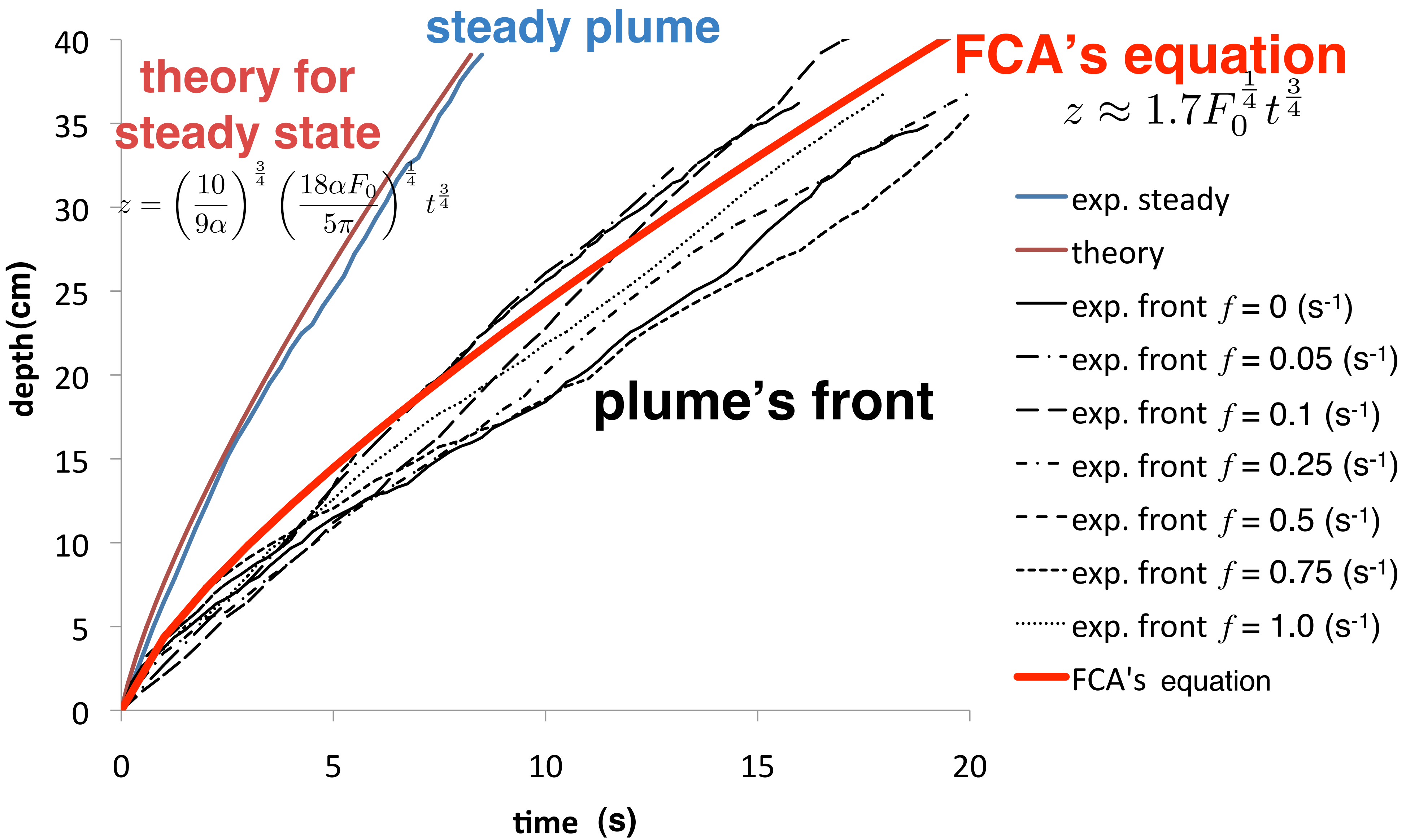
- Fernando, Chen, and Ayotte (1998) also showed that the front of an axisymmetric turbulent plume descends as

$$z \approx 1.7 F_0^{\frac{1}{4}} t^{\frac{3}{4}}$$

$$\frac{z}{F_0^{\frac{1}{4}}\Omega^{-\frac{3}{4}}}$$



time vs. depth



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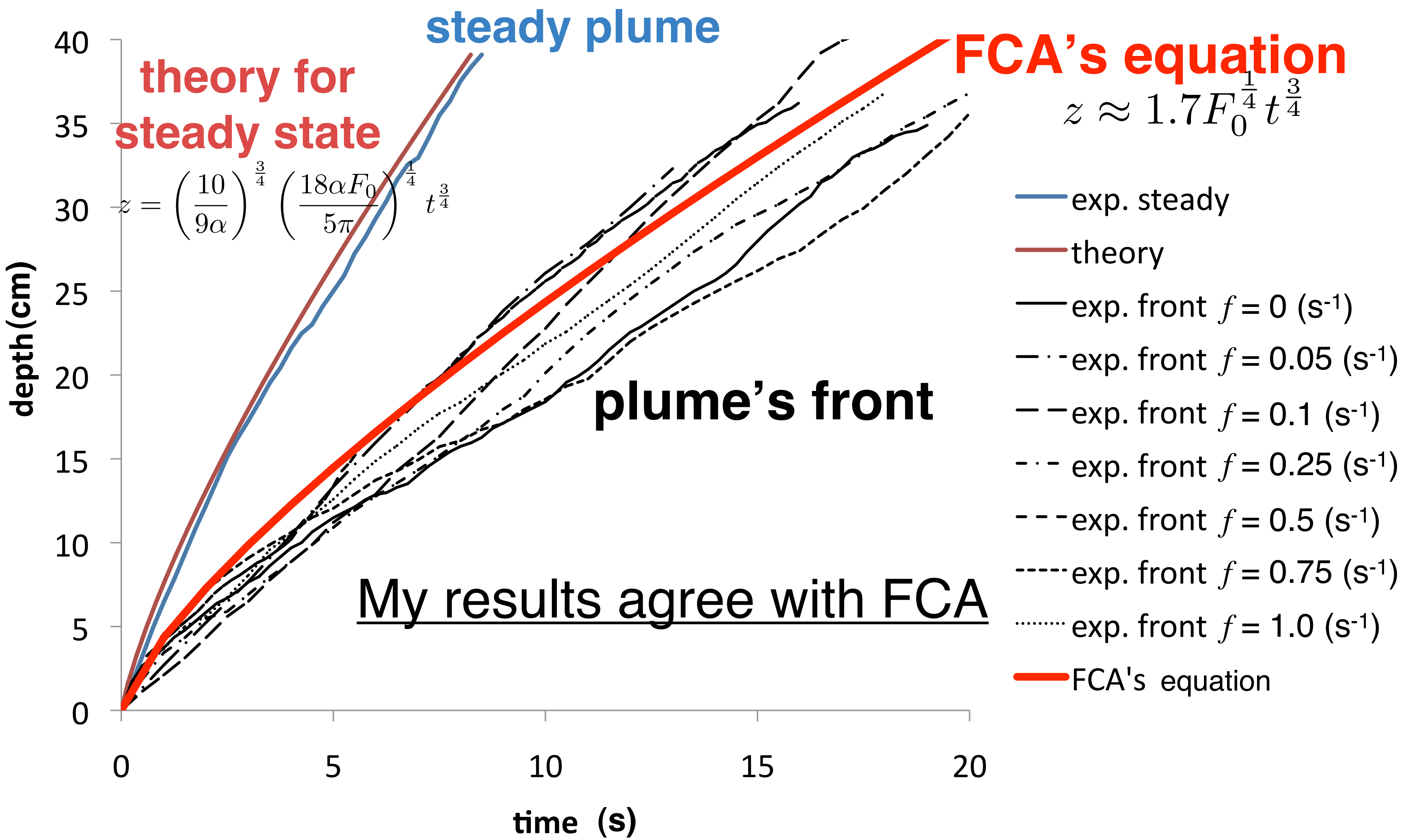

Depth where plumes feel rotation

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- Therefore the depth z_f where plumes feel rotation effects is

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- Therefore the depth z_f where plumes feel rotation effects is

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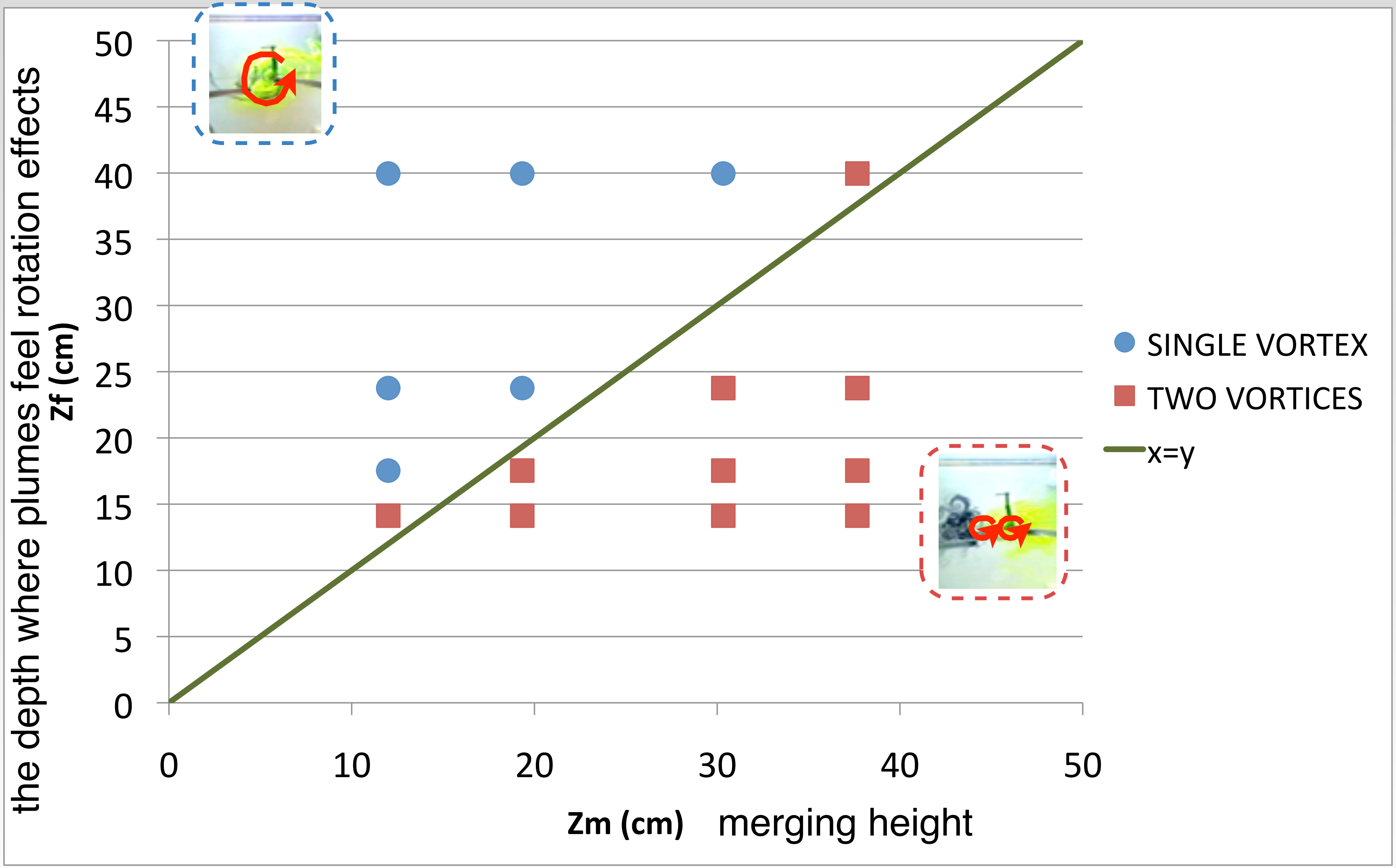
- It is expected that

$z_m < z_f \longrightarrow$ SINGLE VORTEX

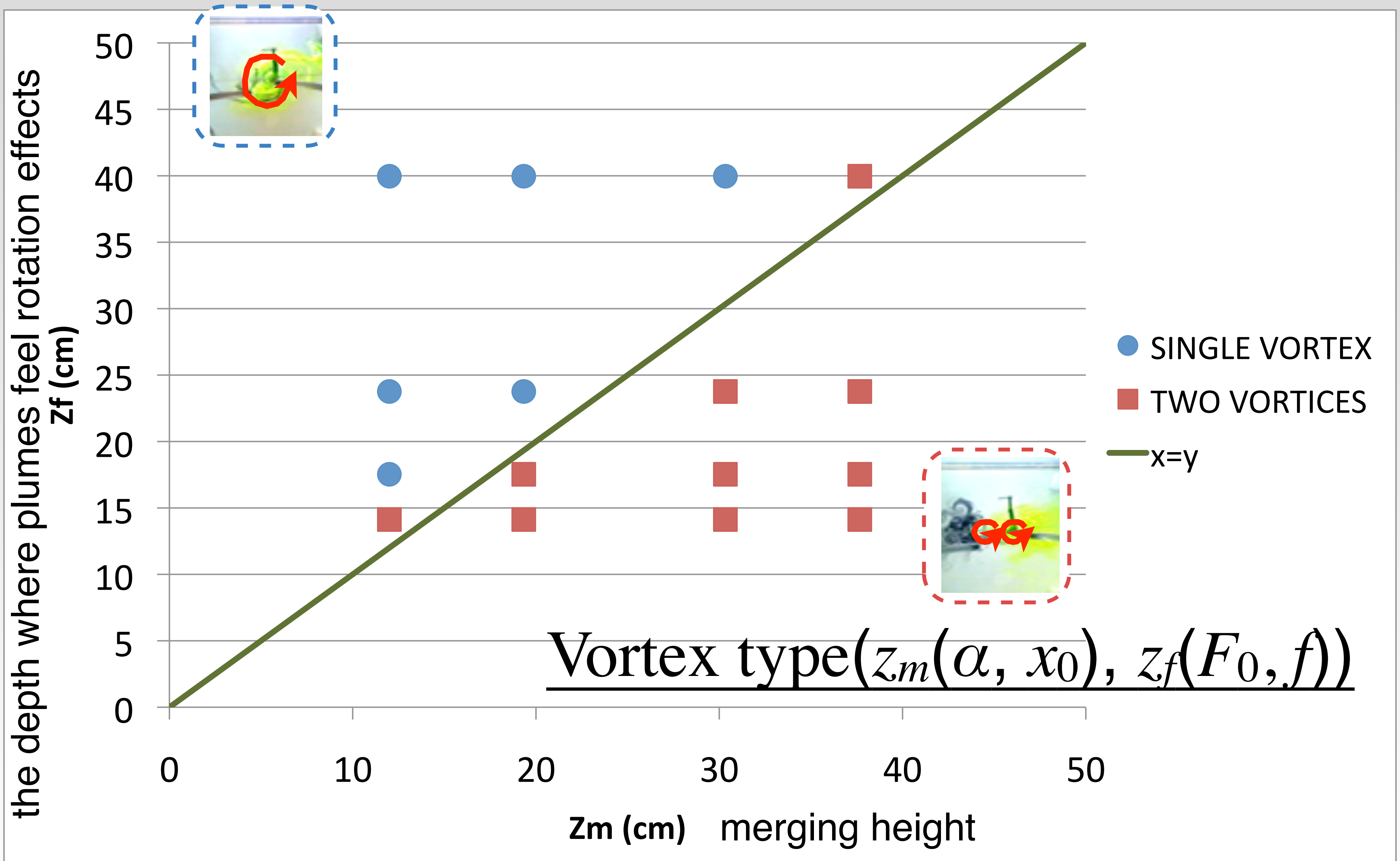
$z_m > z_f \longrightarrow$ TWO VORTICES

(z_m : merging height)

Vortices in z_m vs. z_f



Vortices in z_m vs. z_f



$\underline{\text{Vortex type}(z_m(\alpha, x_0), z_f(F_0, f))}$

Summary

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謝辞

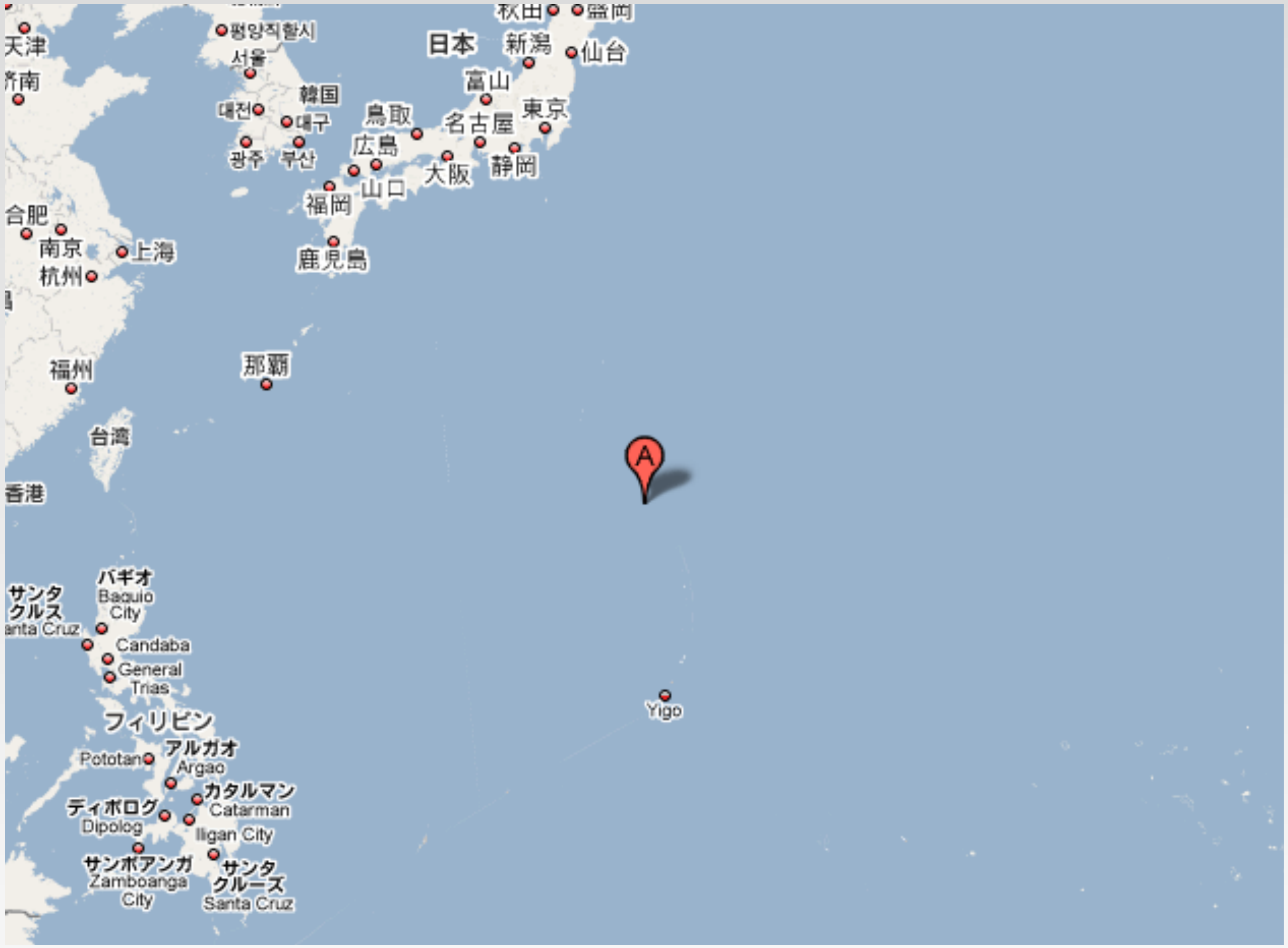
- GFDへは神大・北大GCOE/CPSの派遣事業の支援を受けて参加いたしました。
- 林先生をはじめ、関係者の皆様に厚くお礼申し上げます。

ご清聴ありがとうございました。

(Thank you for your attention.)

Appendix

Northwest Eifuku volcano



Back

Cooper nozzle

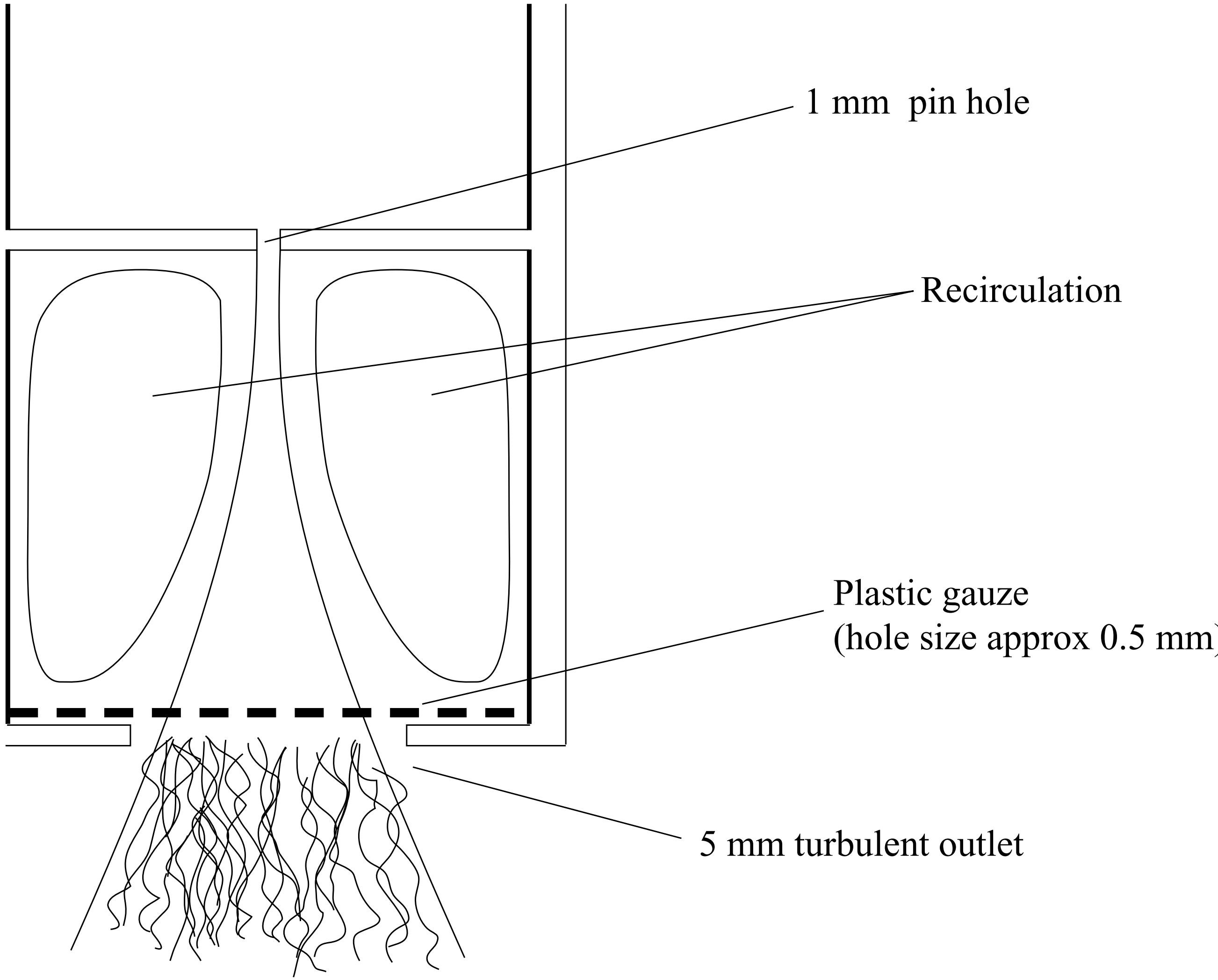
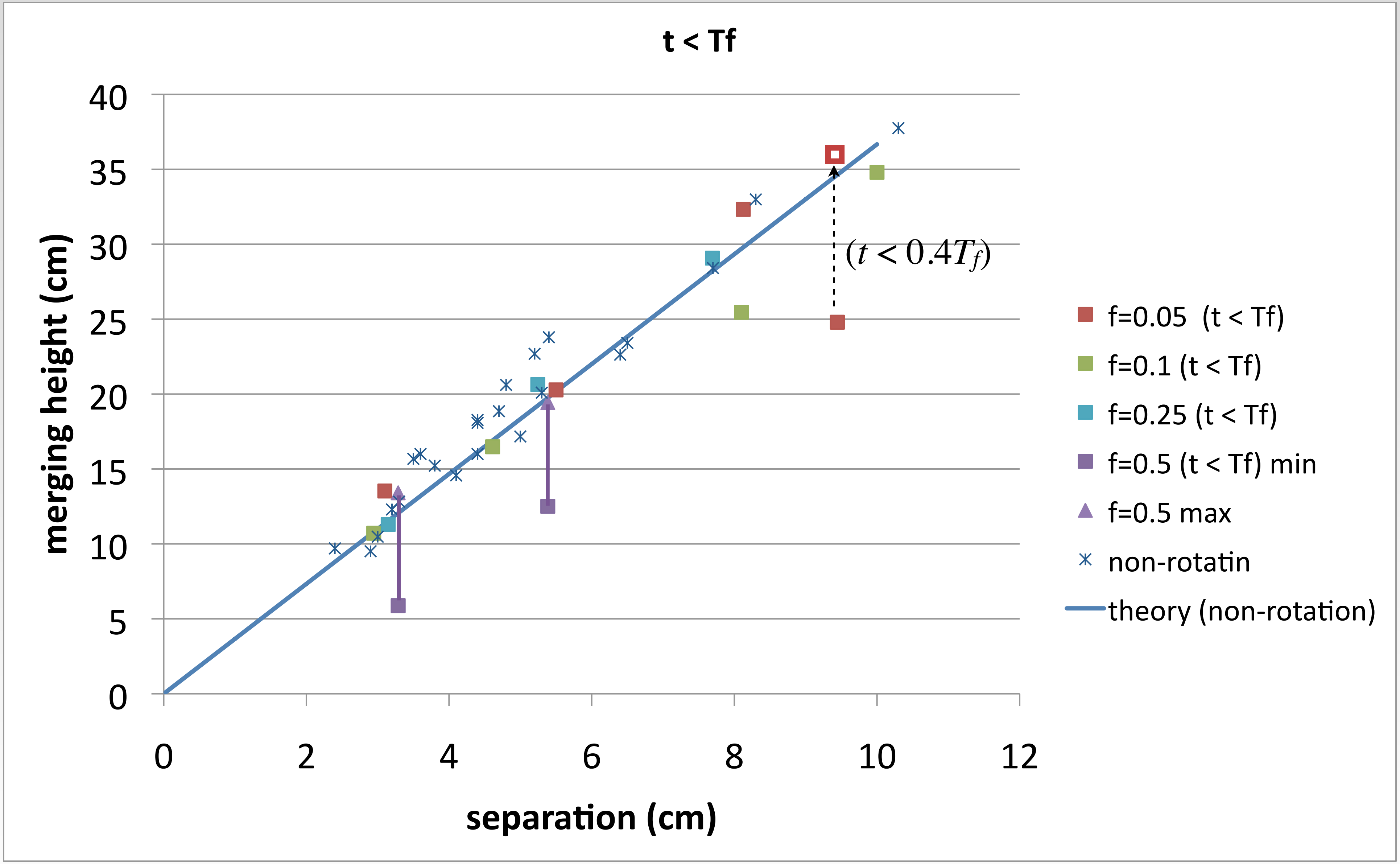


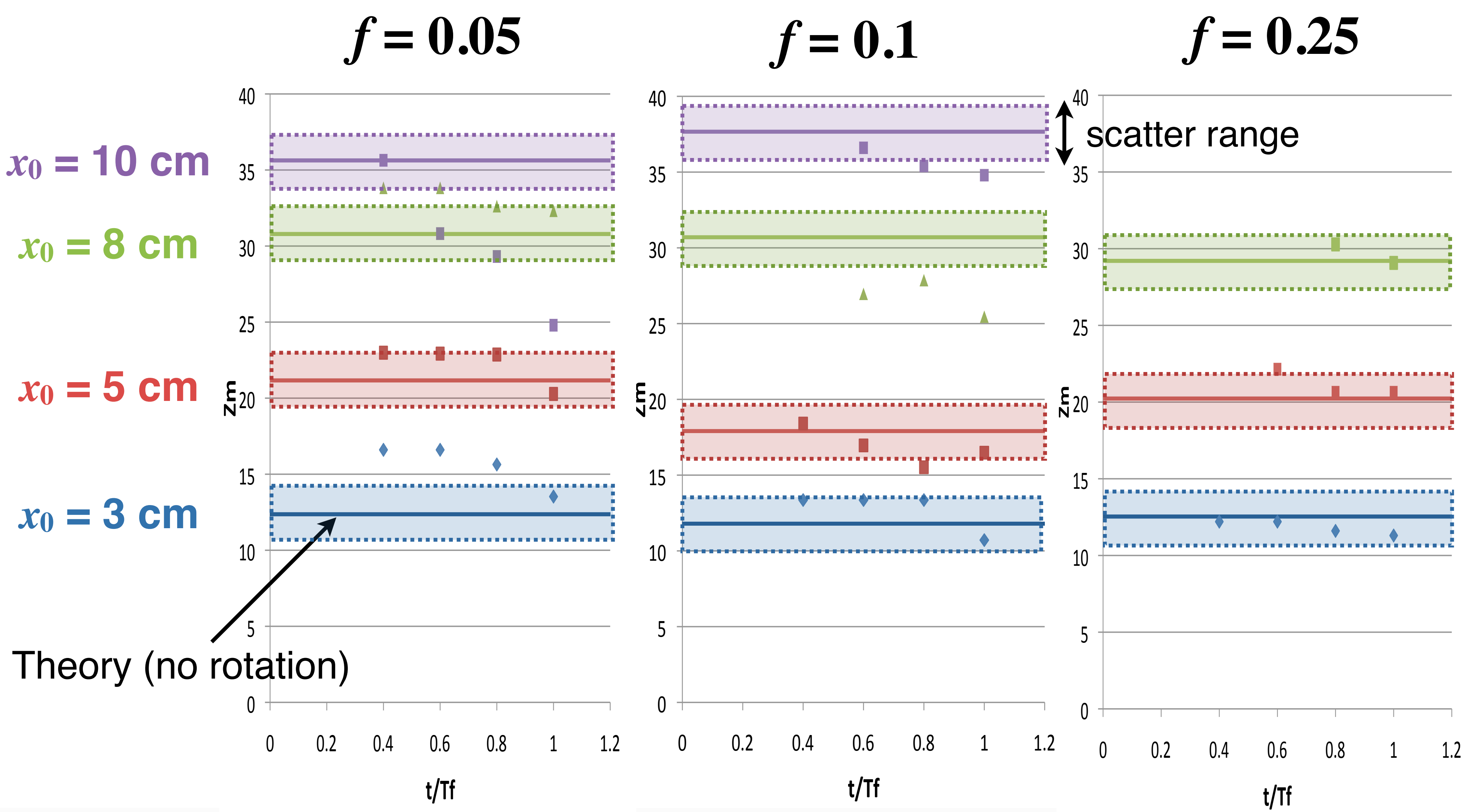
FIGURE 10. Schematic diagram of the Cooper plume nozzle used to produce a turbulent plume source.

Merging height before T_f



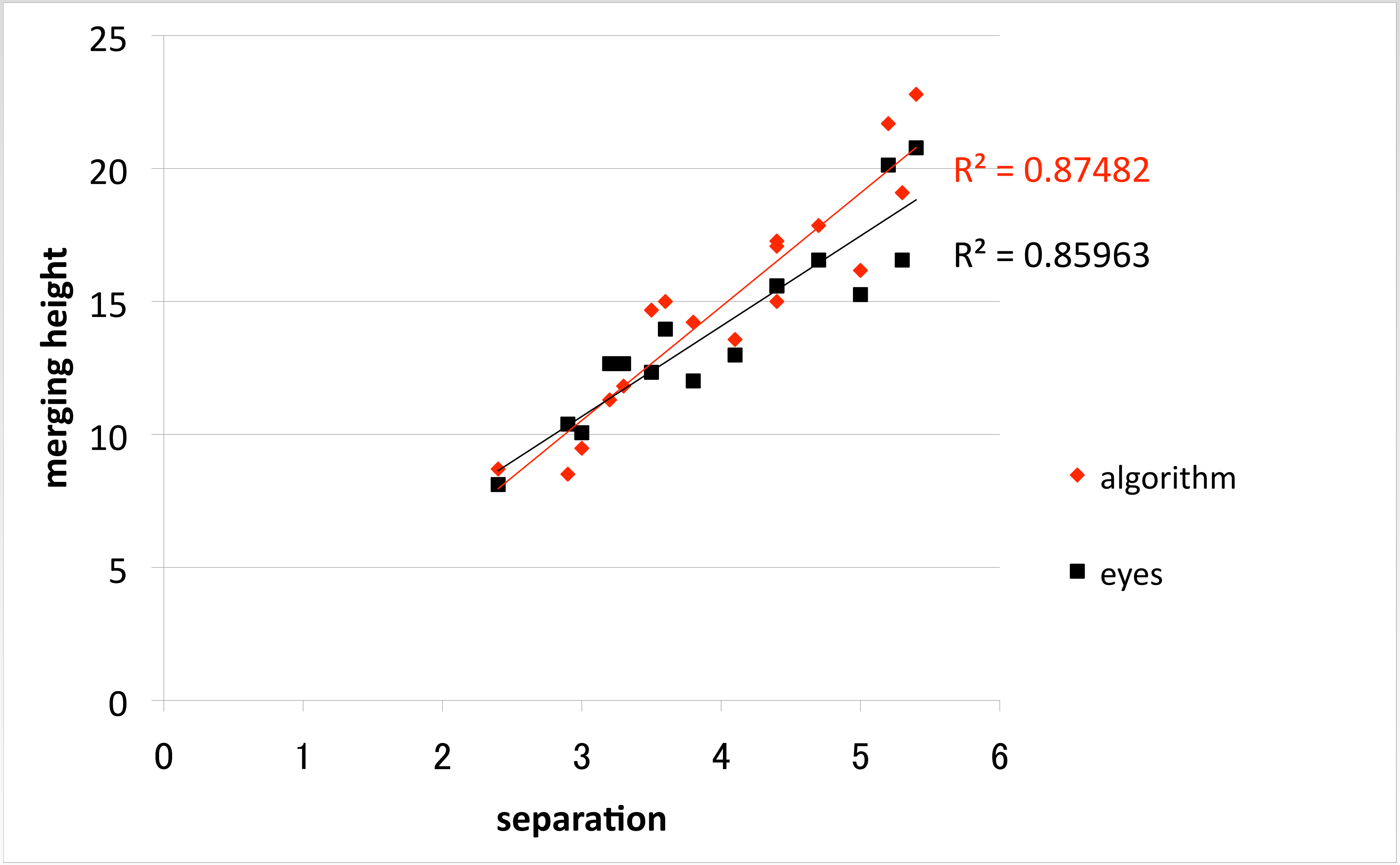
scatter: no-rotation 1.85 cm, rotation 2.08 cm

Dependence of merging height on averaging time

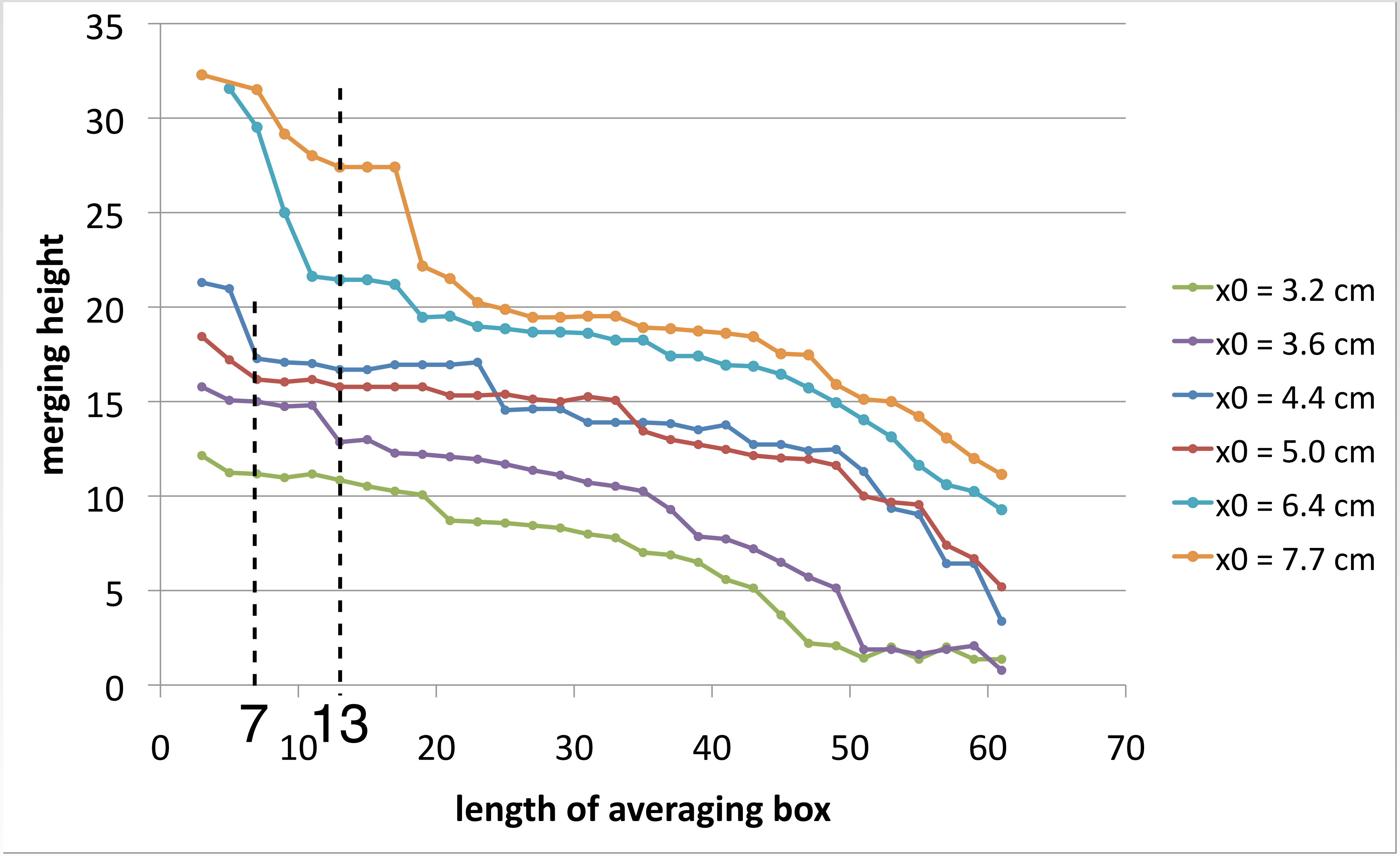


When $t < T_f$ merging height is similar to non-rotating case

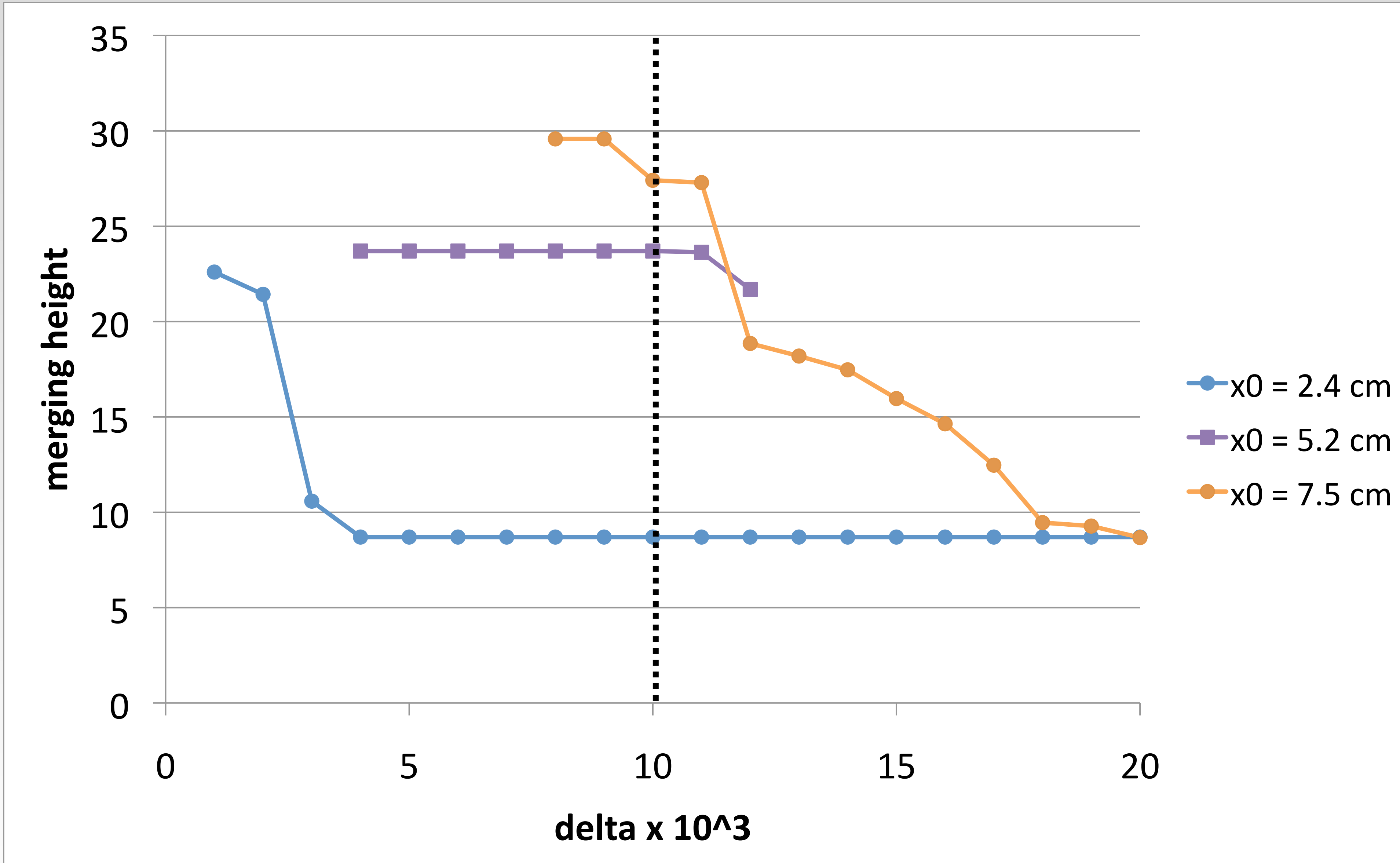
by eyes vs. by algorithm



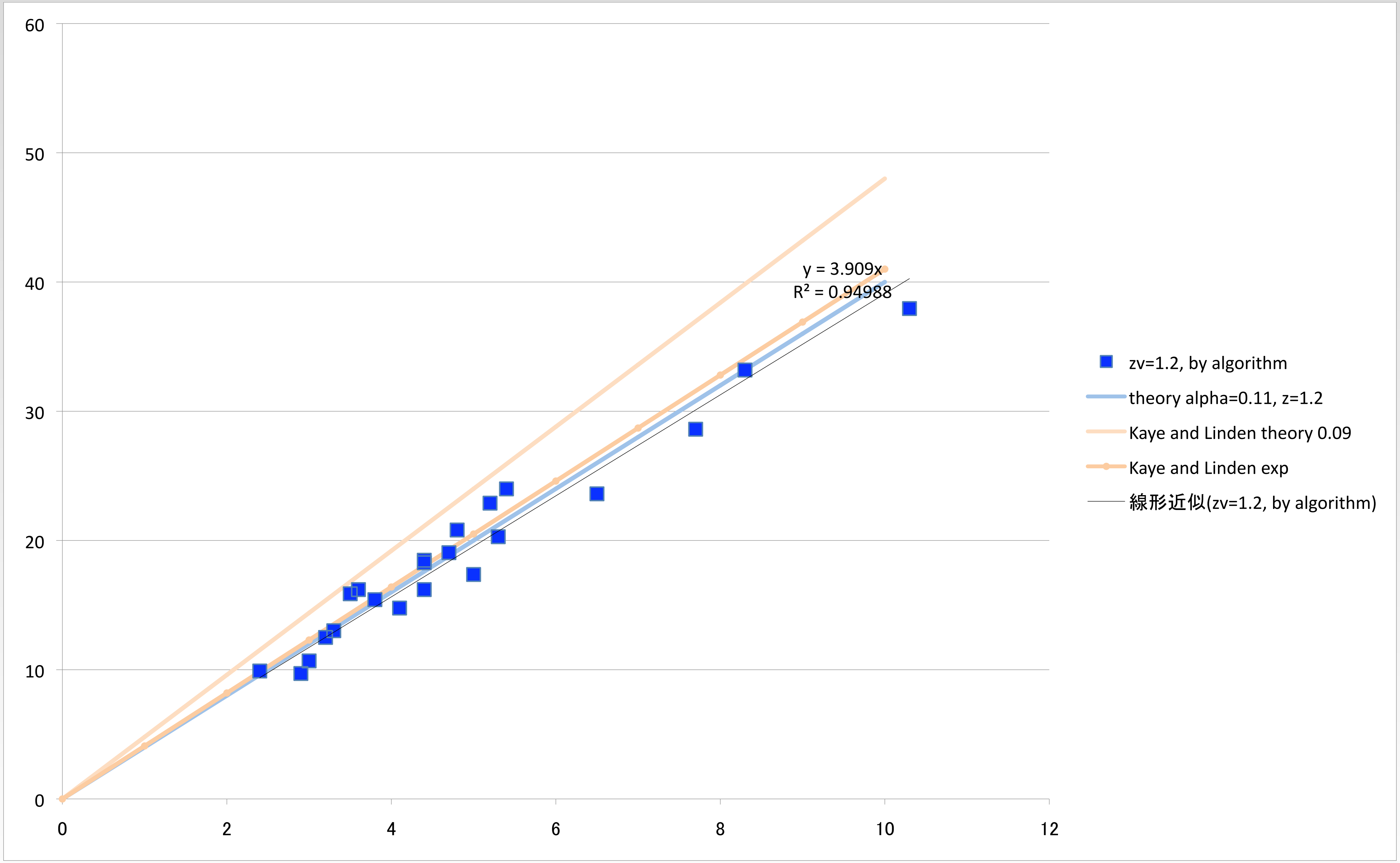
Zm Dependence on the length of averaging box



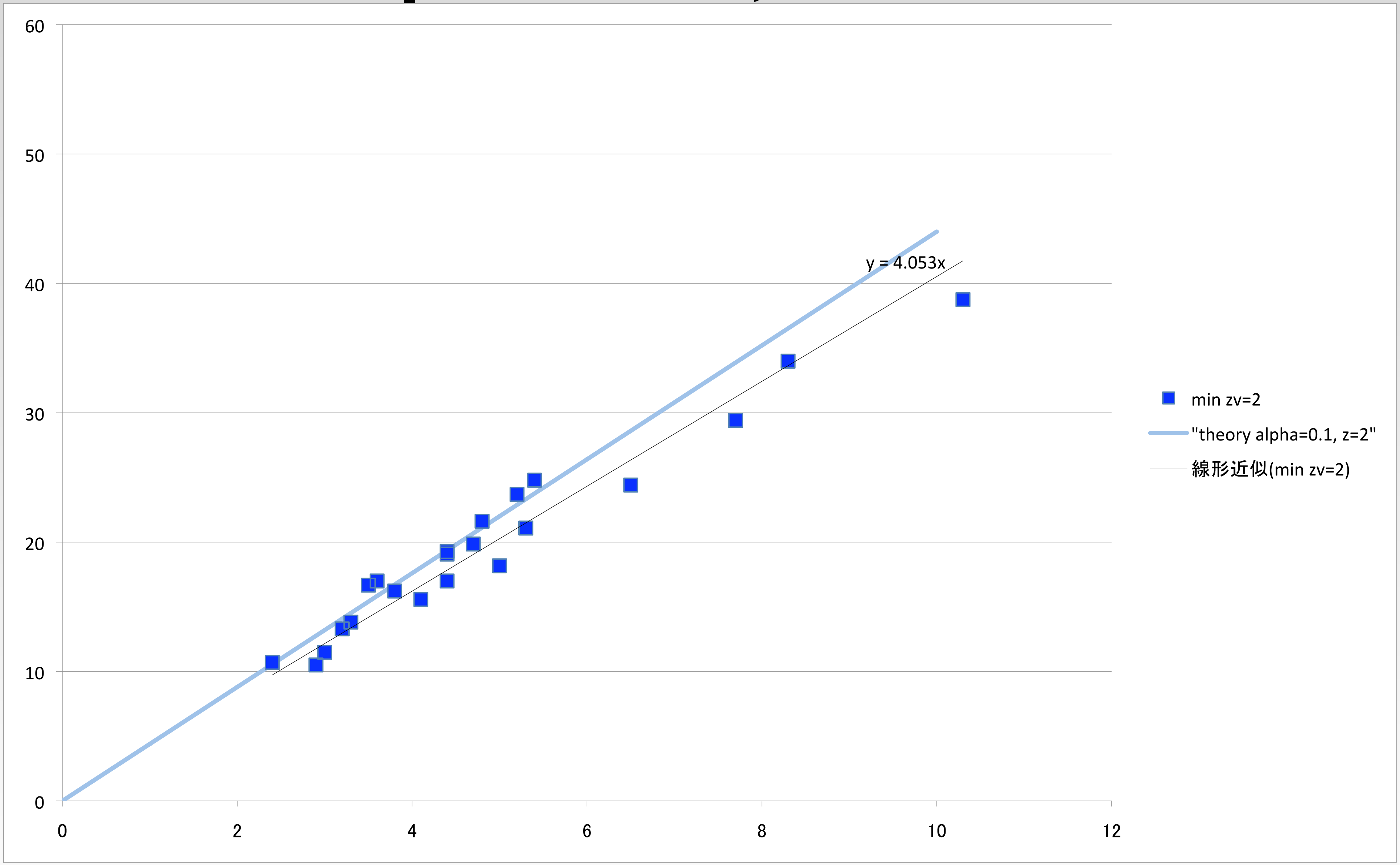
Zm Dependence on delta



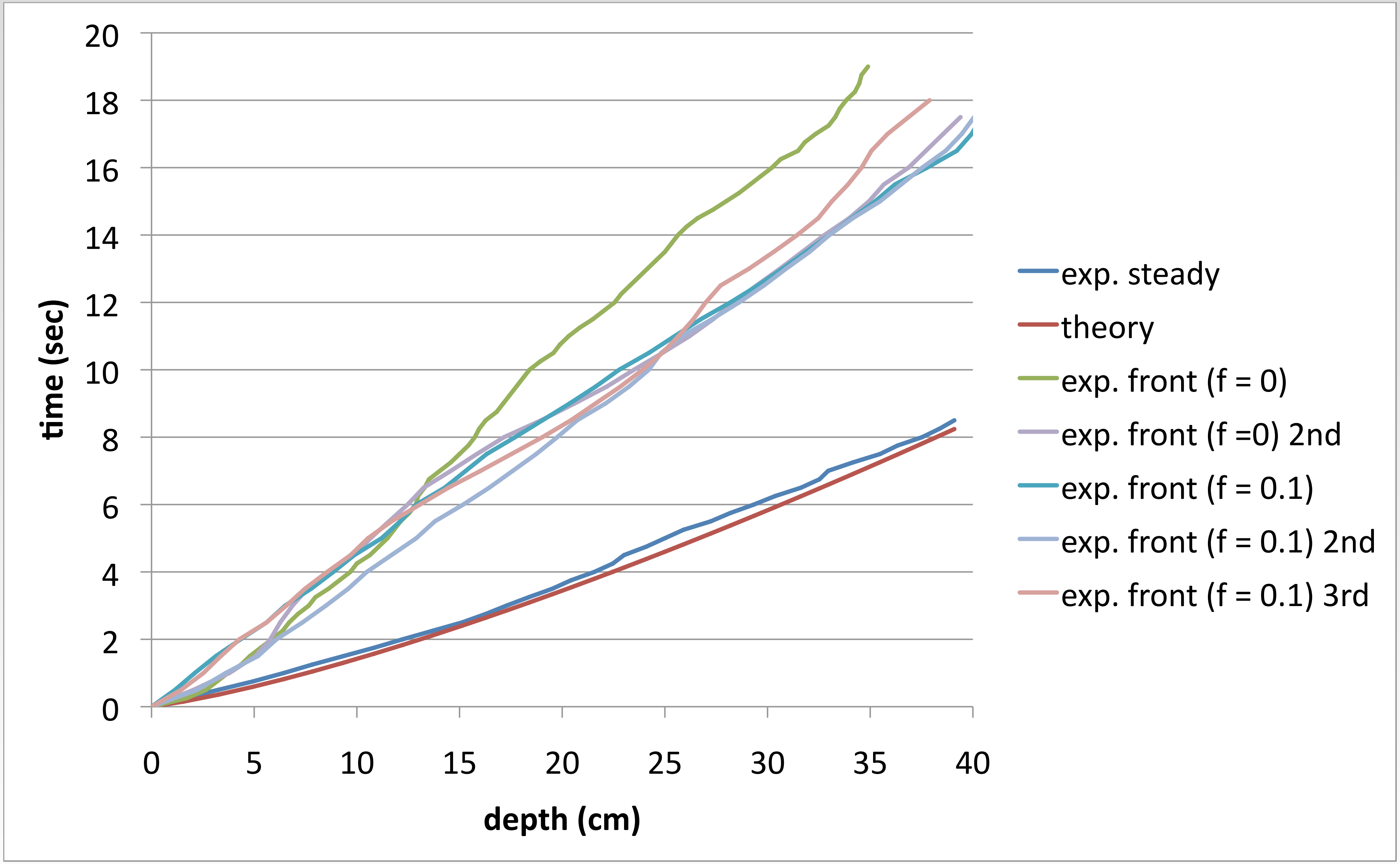
if alpha = 0.11, zv = 1.2 cm



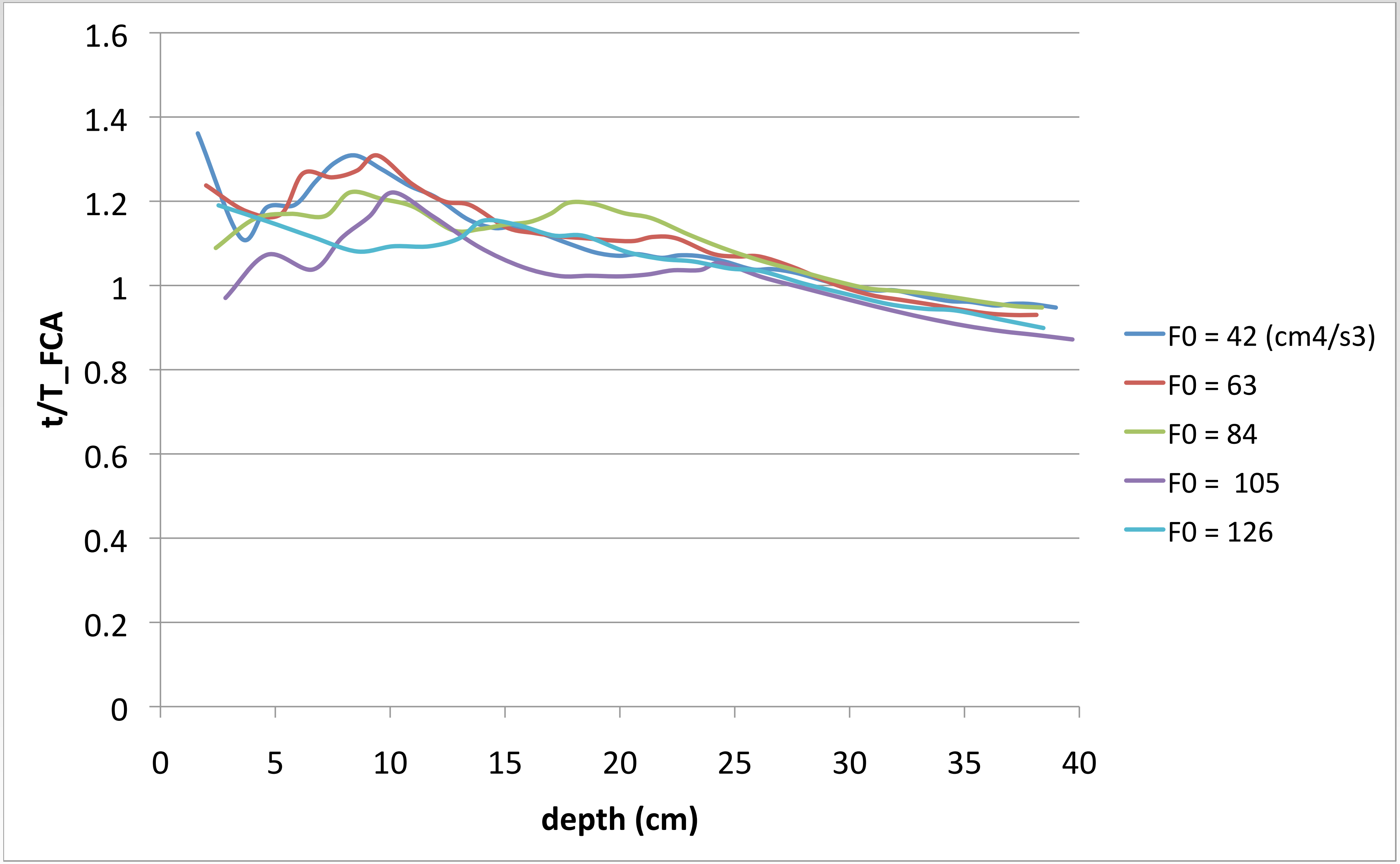
if alpha = 0.1, zv = 2 cm

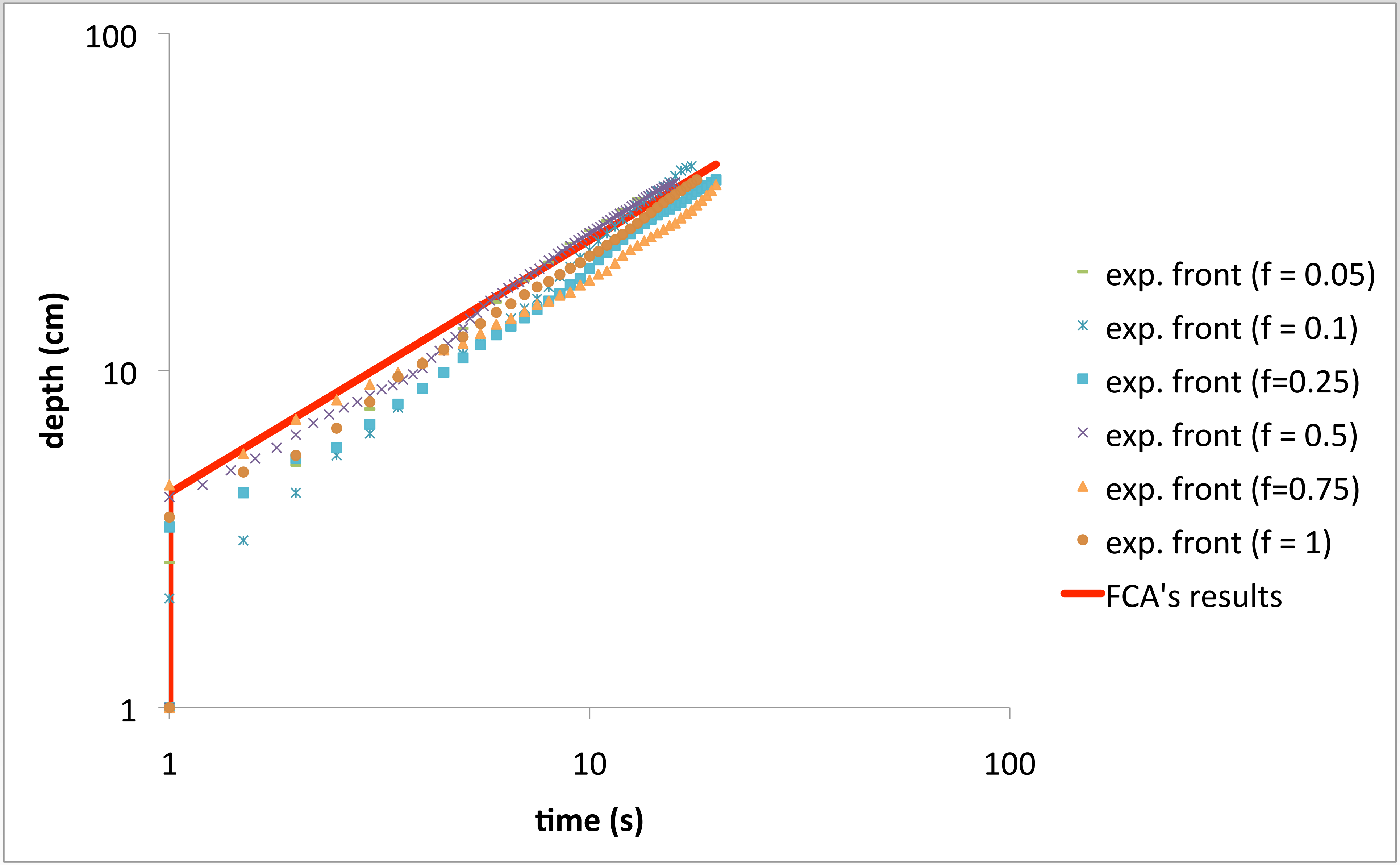


time vs depth

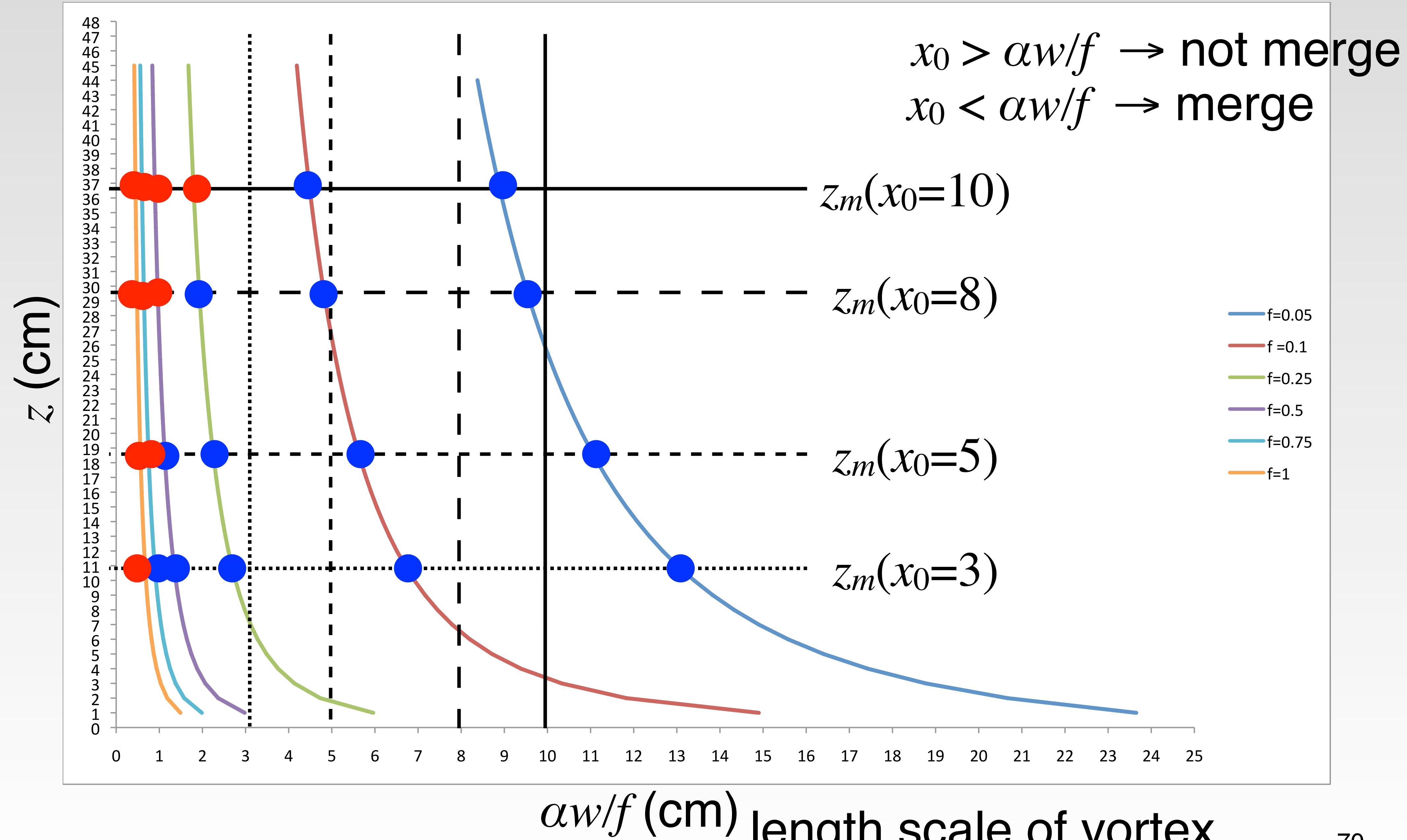


dependency on F_0




100
10
1
depth (cm)
1
10
100
time (s)
exp. front (f = 0.05)
exp. front (f = 0.1)
exp. front (f=0.25)
exp. front (f = 0.5)
exp. front (f=0.75)
exp. front (f = 1)
FCA's results

Length scale of vortex vs. depth



length scale of vortex