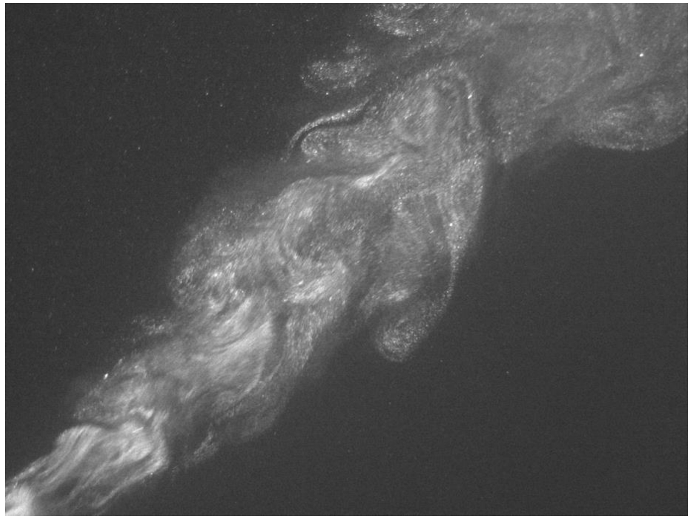
An experimental setup for thermal jets dispersion analysis



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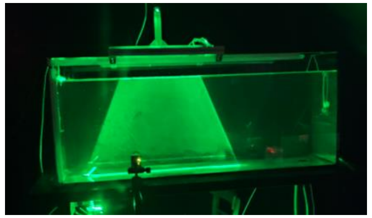
Workshop on Advanced measurement Techniques for Experimental Research

W.A.T.E.R. Summer School

IBW-PAN, Gdansk, 1-5 September



Hands-on event dedicated to experimental methods and advanced measurement techniques

Highlights of 2025 edition

- ✓ **Field measurements at Lubiatowo**
- ✓ **Experimental setups for Particle Image Velocimetry, Ultrasonic Velocity Profilemeter, Particle Tracking Velocimetry, Laser Doppler Velocimetry, Temperature measurements, bathymetry and Acoustic Doppler Current Profiler**
- ✓ **Large scale experiment: dune erosion**
- ✓ **Master classes for the particpants**

Apply at www.watersummerschool.wordpress.com

Early bird: 31 May 2025

UBERTONE Eurotek International DANTEC DYNAMICS AQUATEC RICHARD LOUNSBERY FOUNDATION EST. 1959 IAHR International Association for Hydro-Environment Engineering and Research

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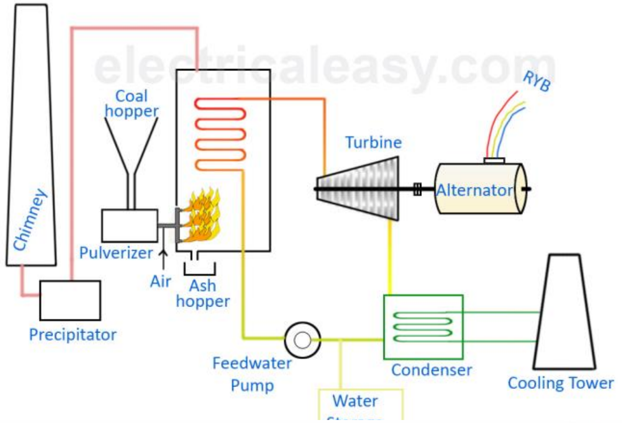
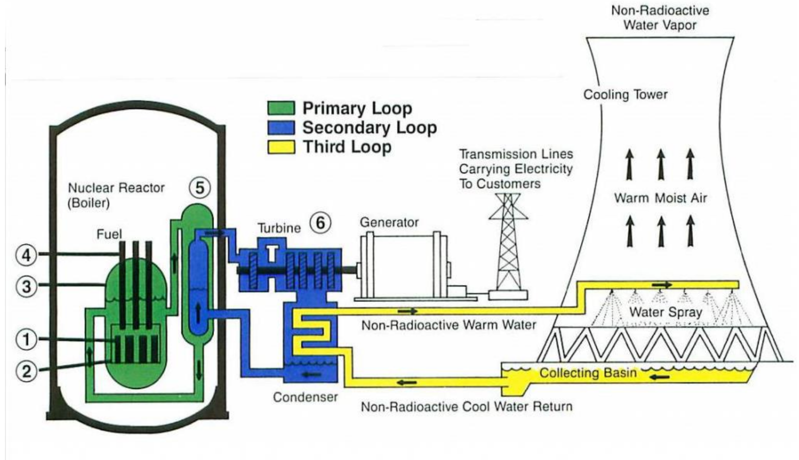
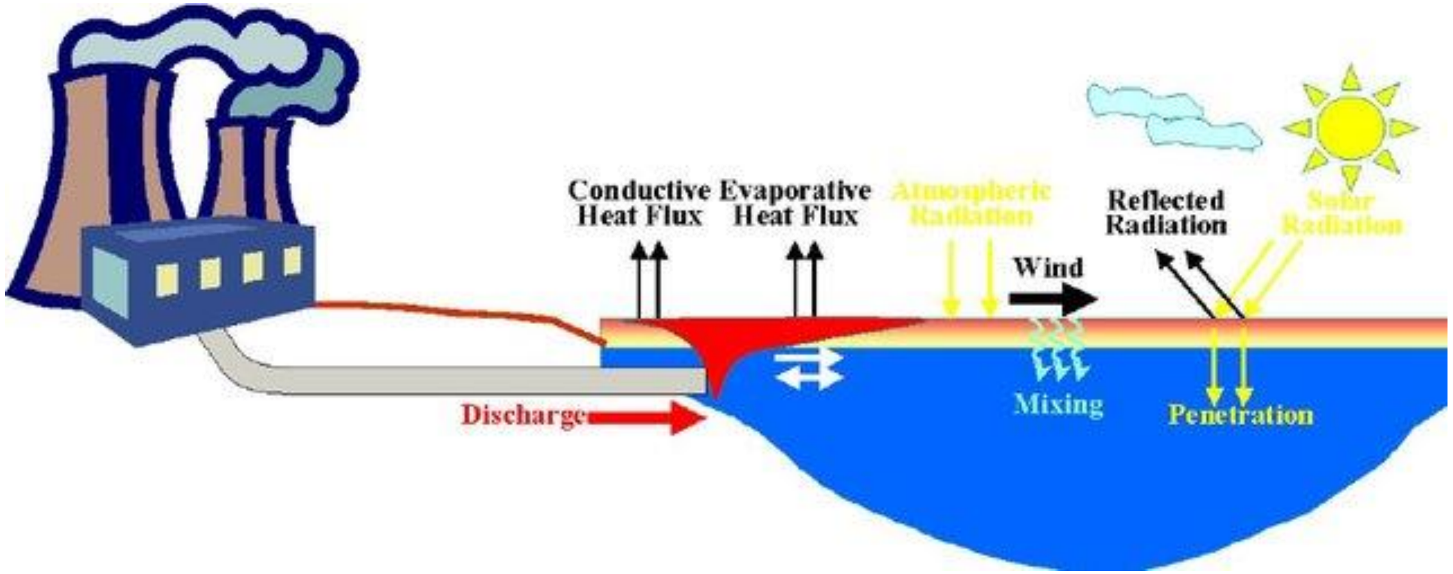
Motivation

Thermal based power plants (coal or nuclear) need a cooling system.

Cooling towers are often used but other solutions may consider discharging **hot water in the environment (rivers, lakes, sea)**.







Coal: https://www.electricaleasy.com/2015/08/thermal-power-plant.html

Nuclear: www.google.com/url?sa=i&url=https%3A%2F%2Fwww.qats.com%2Fcms%2F2016%2F10%2F07%2Findustry-developments-cooling-nuclear-power-plants%2F&psig=AOvVaw3tCql90CCPnQ3btgVbPC1V&ust=1695228468911000&source=images&cd=vfe&opi=89978449&ved=0CBIQjhxqFwoTCOjEhKiQt4EDFQAAAAAdAAAAABAE

Motivation

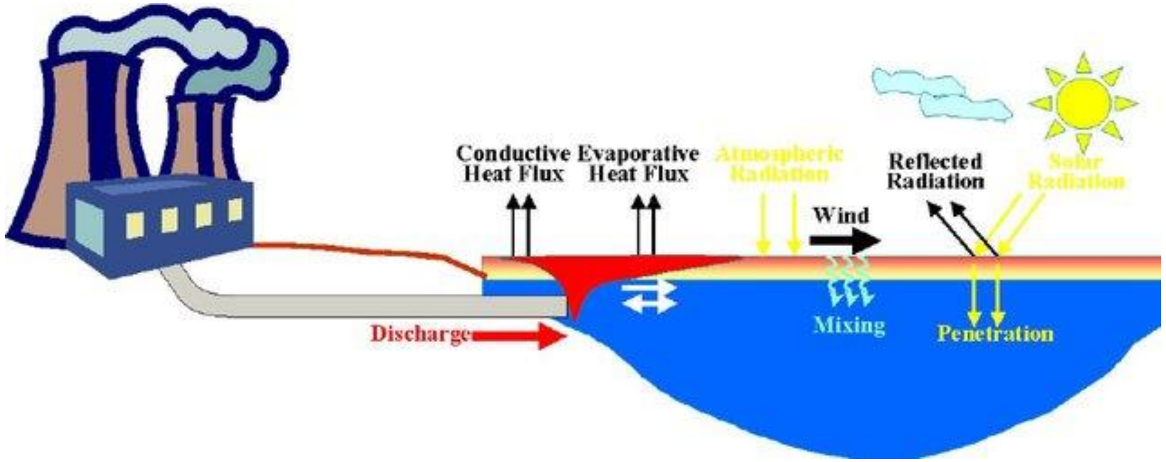
Discharging hot water in the environment may cause severe problems to the flora and fauna:

As temperatures increase, **green algae and diatoms are replaced by cyanobacteria**.

One of the key issues in thermal pollution is the **replacement of cold-water fishes with warm-water fishes**.

Rapid changes in temperature associated with power plant operations can kill fishes by thermal shock (Ottinger et al.,1990).

Mitigating the thermal effects of power plant effluent obviously has a significant financial cost (Dodds et al. 2010)



Thermal jets (Turbulent buoyant jets)

1. A **jet is a shear flow** (Baines and Chu, 1996) that is **generated by a continuous momentum source** (Lee and Chu, 2003). The momentum flux, M, can be defined as:

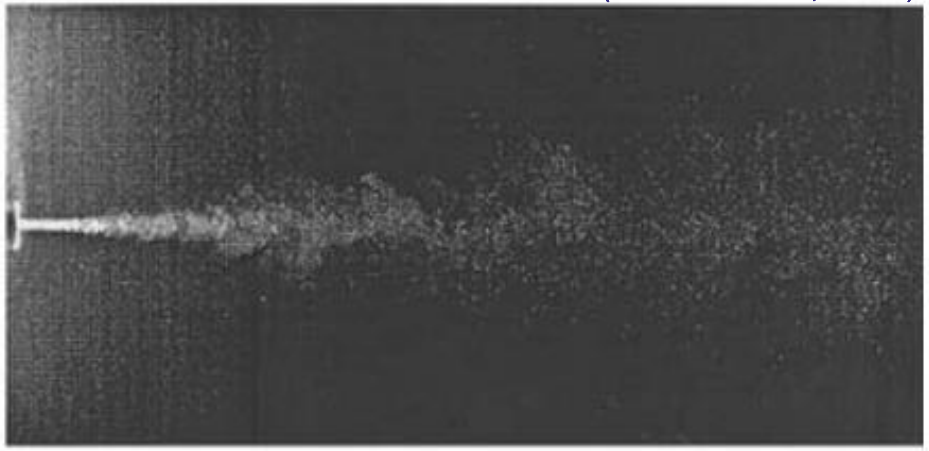
$$M = \int_S (\rho\, \mathbf{v})\mathbf{v} \cdot \mathbf{n} dS$$

2. A plume on the other hand is a **flow controlled by buoyancy** that is generated by a continuous buoyancy source, such as a heated plate. A plume tends to have lower density and greater dispersion, with the fluid spreading out over a larger area (Morton et al., 1956). Buoyancy flux can be written as:

$$B = \left(gd \frac{(\rho_a - \rho_o)}{\rho_o} \right) Q$$

$\rho_a =$ Plume $\qquad \rho_0 =$ Environment

(Kwon and Seo, 2005)

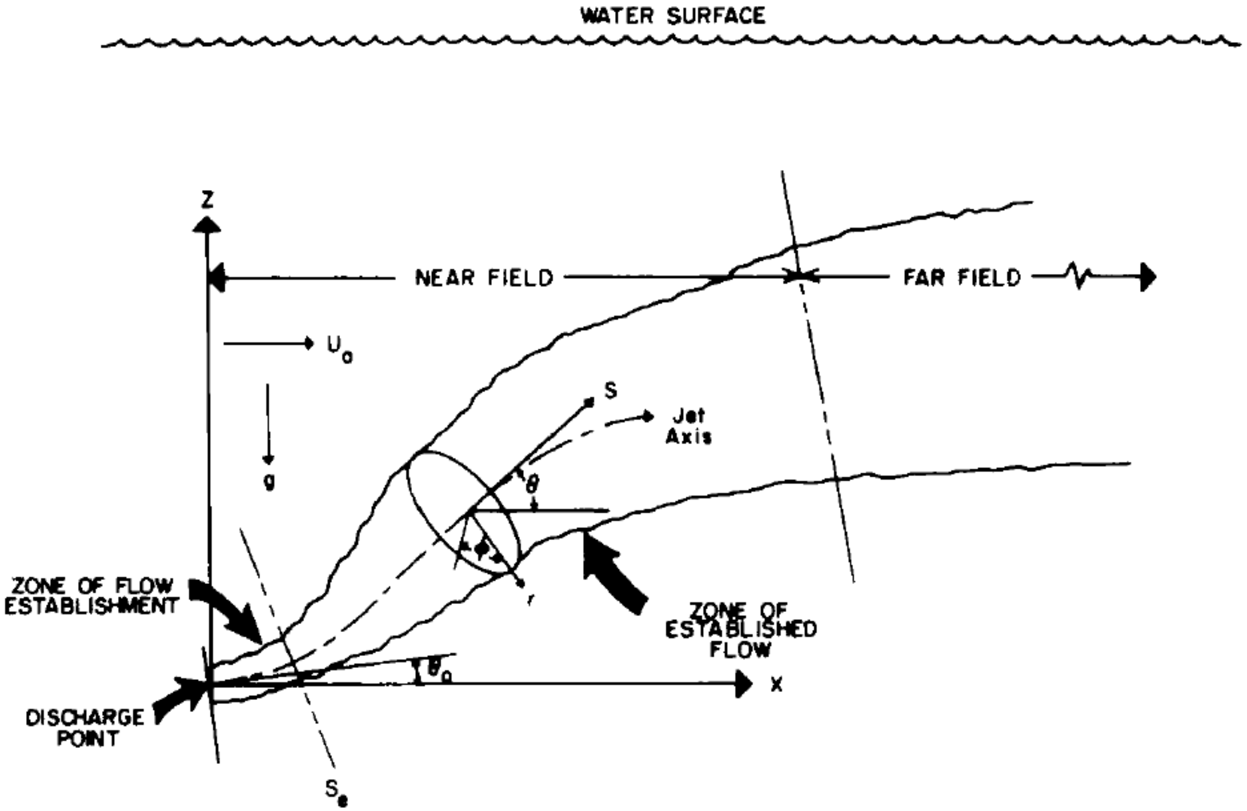


$$\mathrm{Re} = \frac{u_a d}{\nu}$$ Turbulent jet if Re > 2000

(Morton, Taylor, Turner, 1956; List, 1983; Lee and Chu, 2003)

Thermal jet

Jet+Plume: In this case we talk about a turbulent buoyant jet**. Initially it's driven by momentum** and, after a certain distance from the source, **buoyancy becomes dominant**.



Gebhart et al. (1984)

Densimetric Froude number:

$$\mathrm{Fr}_\rho = \frac{U_o}{\left(gd\,\dfrac{(\rho_a - \rho_o)}{\rho_o}\right)^{1/2}}$$

$\dfrac{\text{Momentum}}{\text{Buoyancy}}$

Pure jet

$\mathrm{Fr}_\rho = \infty$

Pure plume

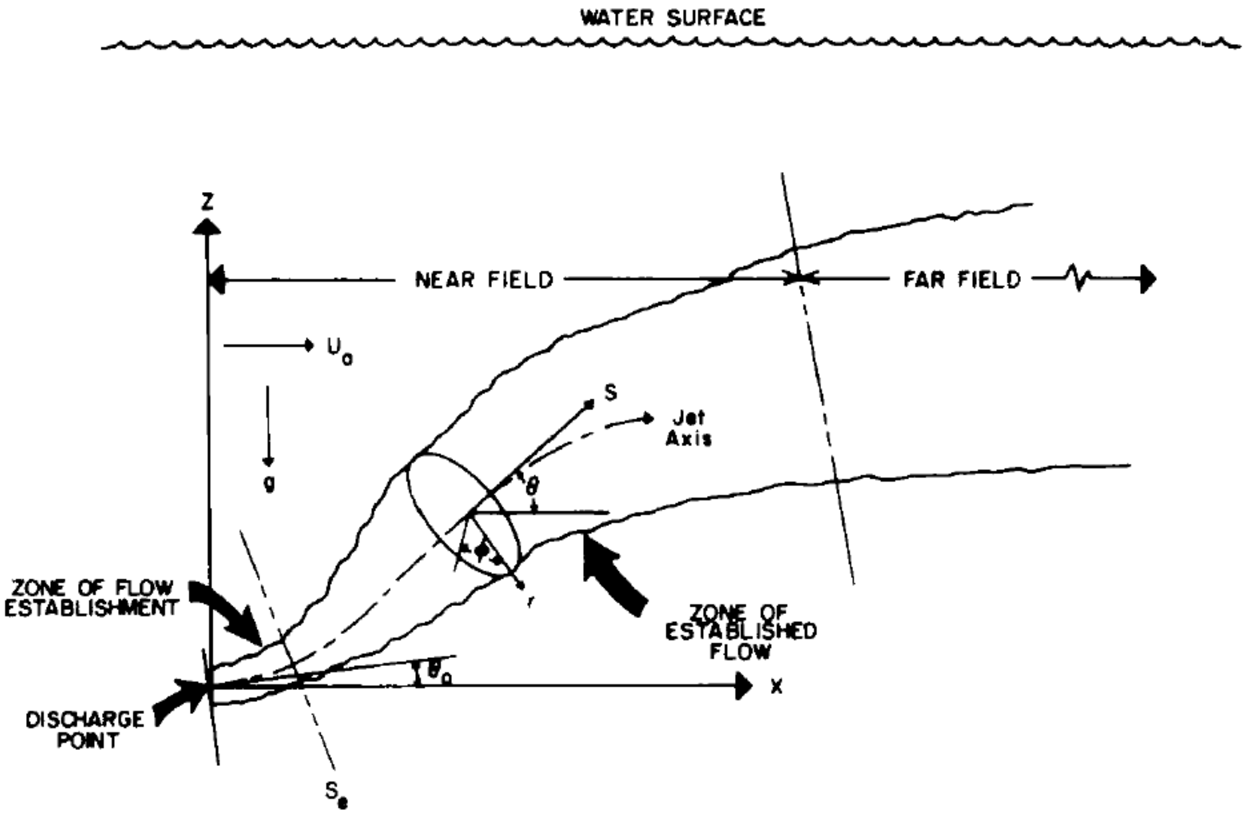
$\mathrm{Fr}_\rho \approx 0$

$$\ell_M = \frac{M^{3/4}}{B^{1/2}}$$

Characteristic length scale describing the the relative importance of momemtum and buoyancy fluxes

Thermal jet

Jet+Plume: In this case we talk about a turbulent buoyant jet**. Initially it's driven by momentum** and, after a certain distance from the source, **buoyancy becomes dominant**.



Gebhart et al. (1984)

Temperature field: To determine the regions of the domain affected by the jet.

Jet trajectory: To determine jet's parameters.

Jet velocity: To determine the velocity field induced by the jet.

To determine the turbulent variables.

Experimental setup

Requirements:

1. Test different jet nozzles geometries.

2. Test different flow rates.

3. Test different temperatures (environment and jet).

4. Easy to modify/improve/change.

5. Test different environmental conditions (e.g.: hydrostatic, stream, periodic-flows).

6. Easy to operate.

7. Affordability.

8. Be repeatable.

Experimental setup

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Want we are looking for:

Gain know-how about theory and experiments on buoyant jets

Define an operation protocol: e.g. continuous vs bursts; run time available

Determine the buoyant jets parameters

Measure the velocity and temperature fields induced by the buoyant jet

Assess the limitations of the physical model and improve (in which conditions the aquarium can be considered *infinite*?)

Experimental setup

Main Ideas:

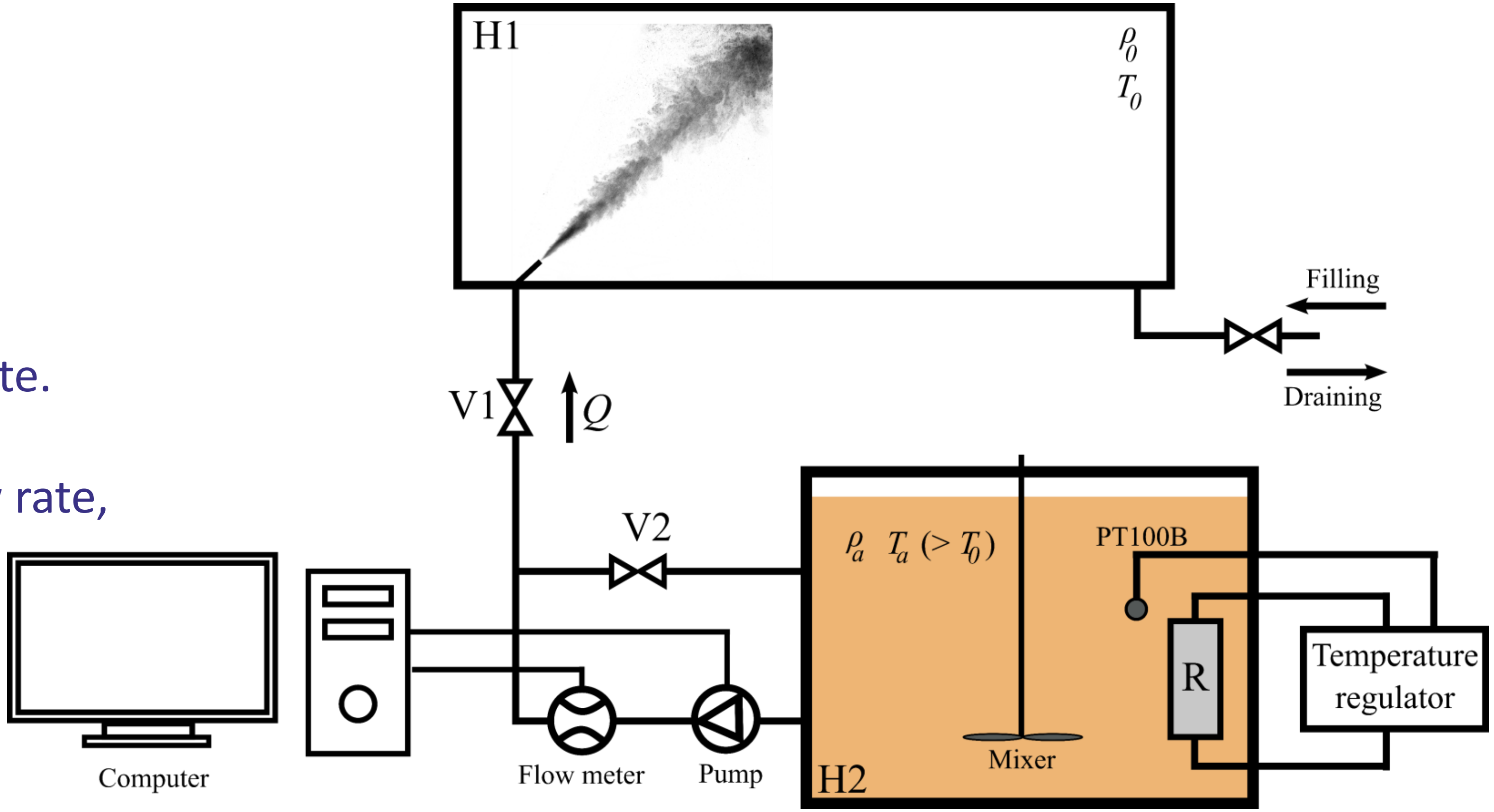
a) One reservoir fto test the jet (H1).

b) One reservoir with hot water (H2)

c) Computer controlled pump: flow rate.

d) Acquistion system to measure: flow rate, temperature, velocity field

e) Modular design



How to implement it?

Experimental setup

Dimensions (length x width x height)

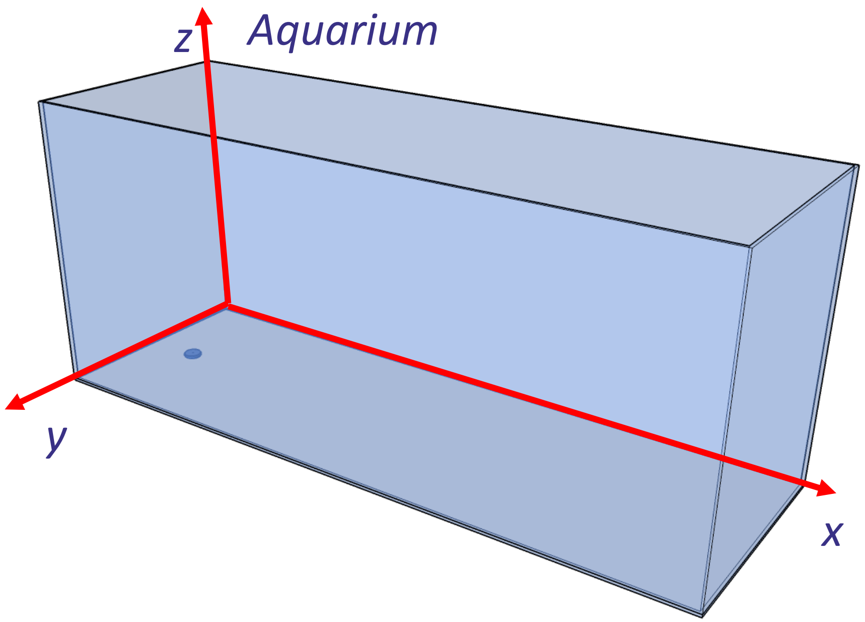
Fan (1967): 2.26 m x 1.07 m x 0.61 m
Saline solutions

Papanicolau and List (1988): 1.15 m x 1.15 m x 3.35 m
Saline solutions

Kwon and Seo (2005): 6.0 m x 1.2 m x 1.0 m
Non-buoyant

***Aquarium from shop:* 1.2 m x 0.4 m x 0.5 m (240 L)**

(Range of nozzle diameters: {1, 3, 5} mm)



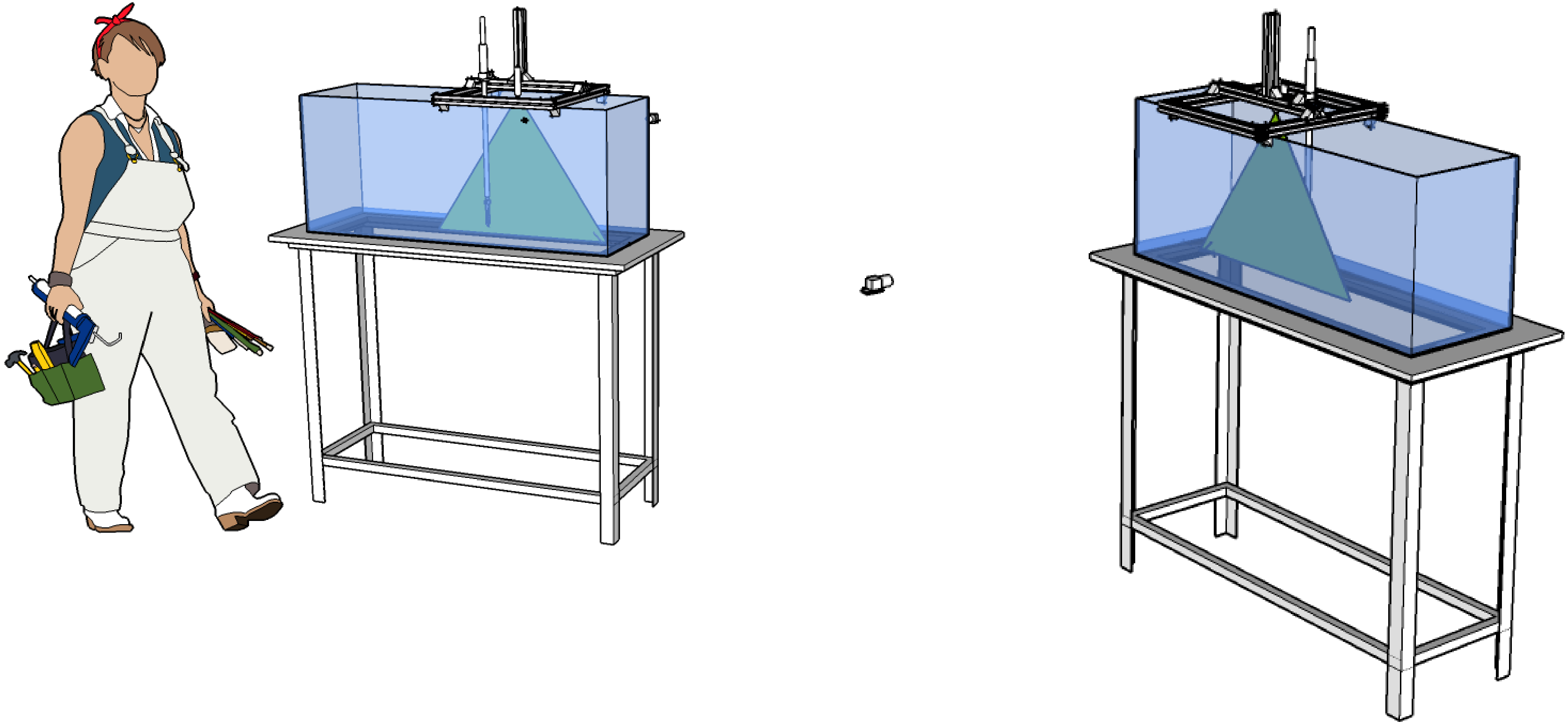
Advantages:

- ✓ Readily available
- ✓ Cost
- ✓ Optical acess
- ✓ Dimensions (easy to modify)

Disadvantages:

- ✓ Dimensions

Experimental setup

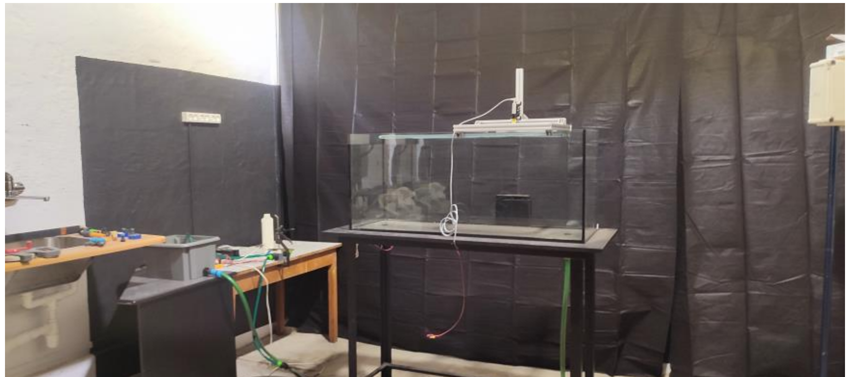


Experimental setup

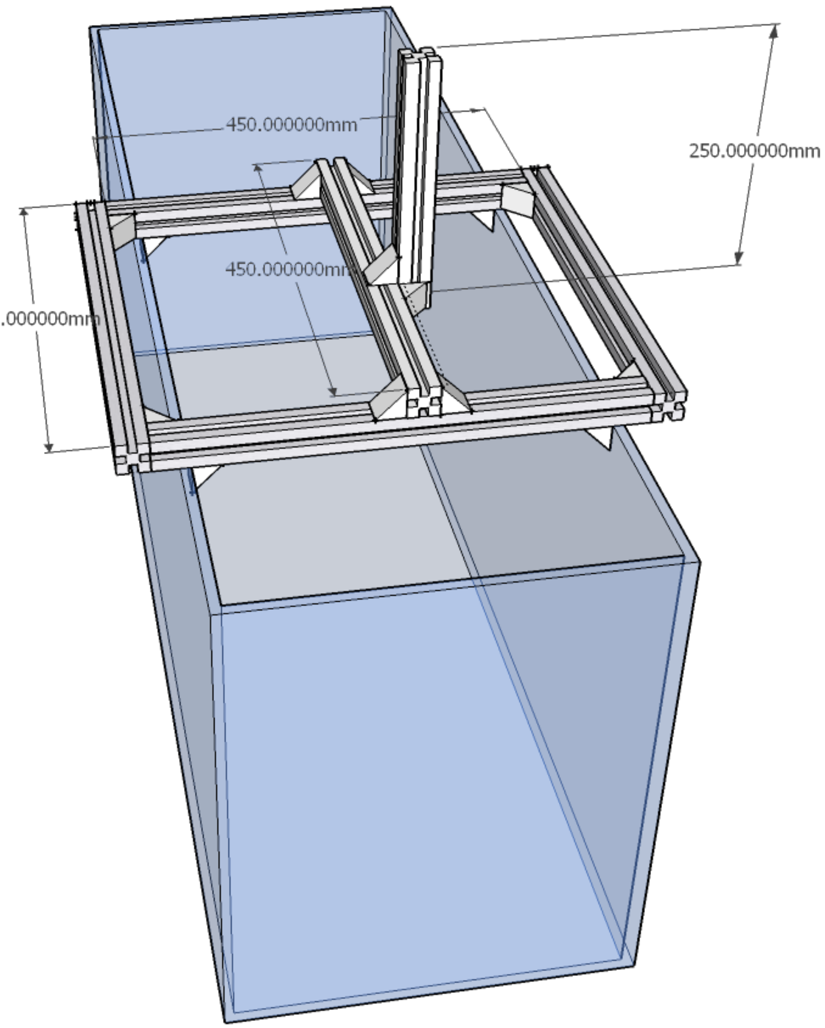


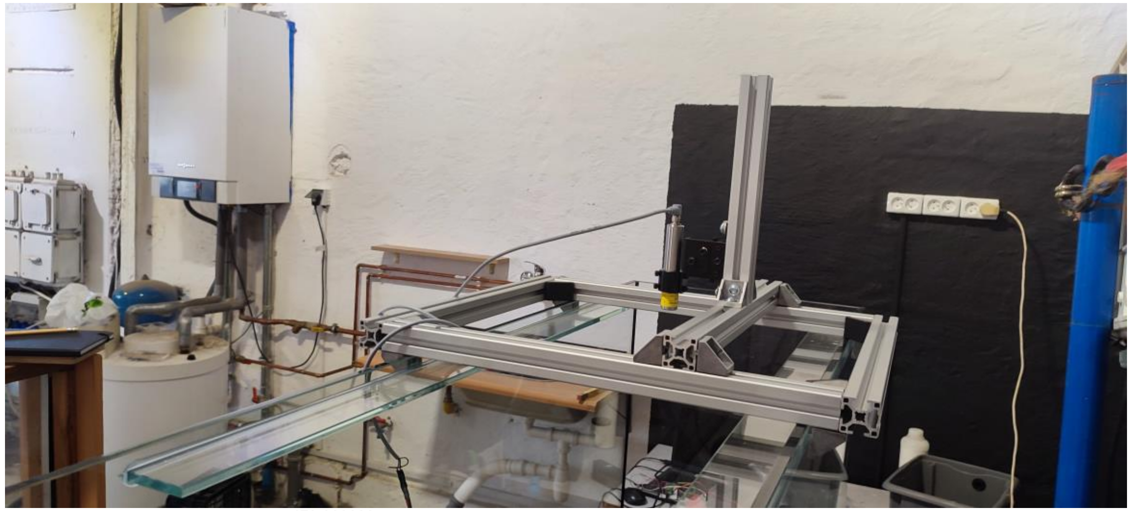


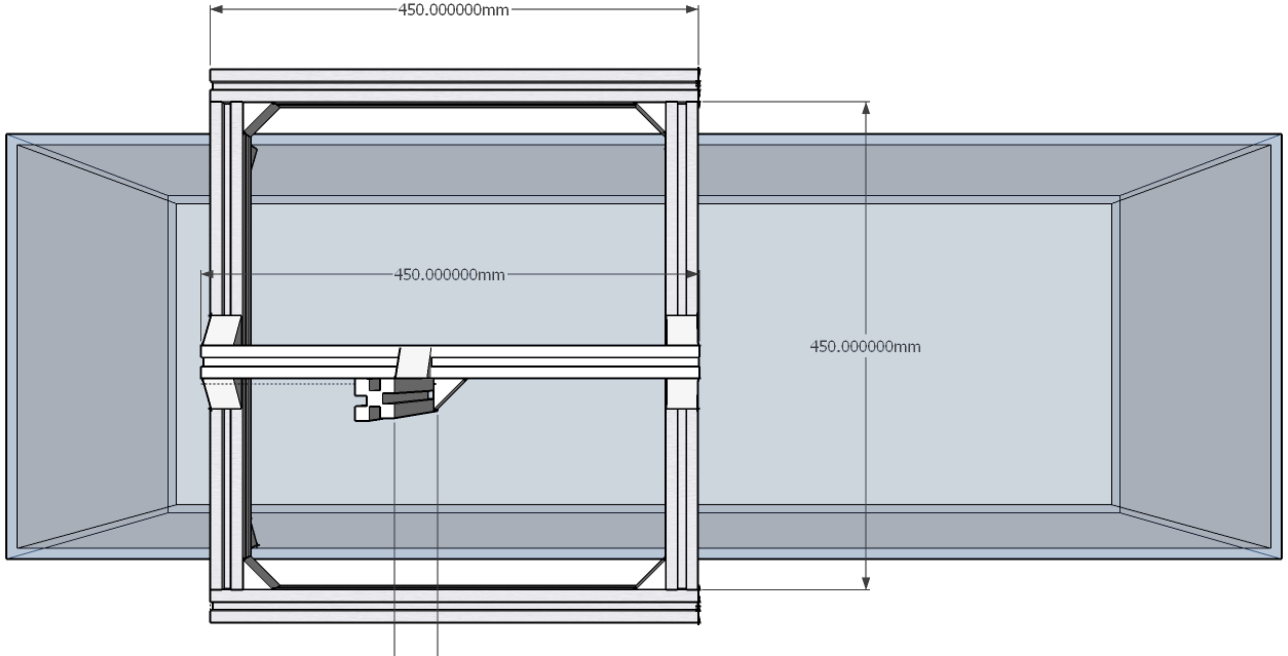



Experimental setup

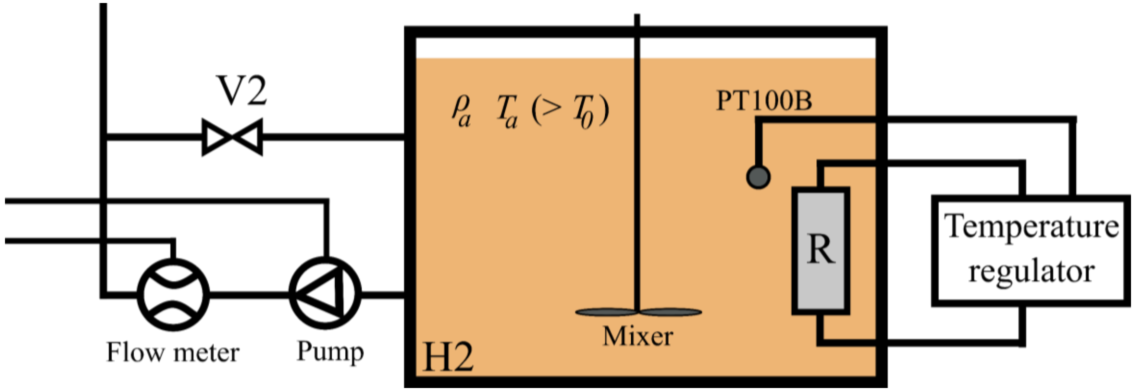






Experimental setup: termal water reservoir

How it started



Experimental setup: termal water reservoir

How it started

Issues:

Hot water from external source

No constant head

Rapid change of temperature T = T(t)

Mixing limited (hand driven)

Experimental setup: termal water reservoir

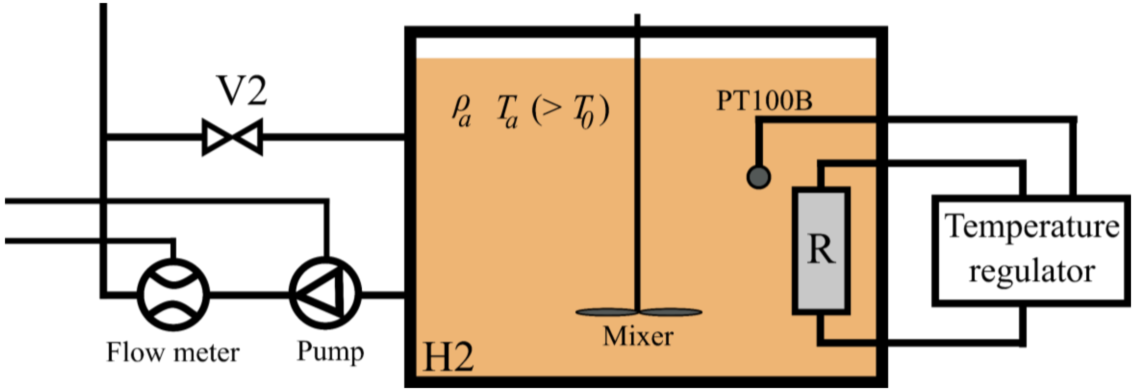
How it's going

Improvements

Constant head through level actioned valve

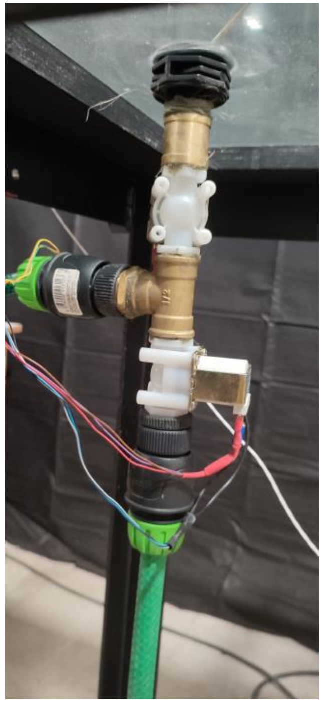
Mixing with motor driven shaft

Proportional-Integral-Diferential (PID) controller to keep the temperature constant ($\pm$ 0.1ºC)

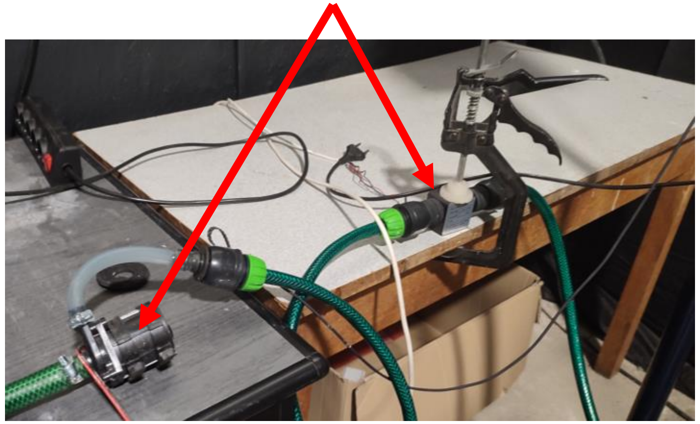


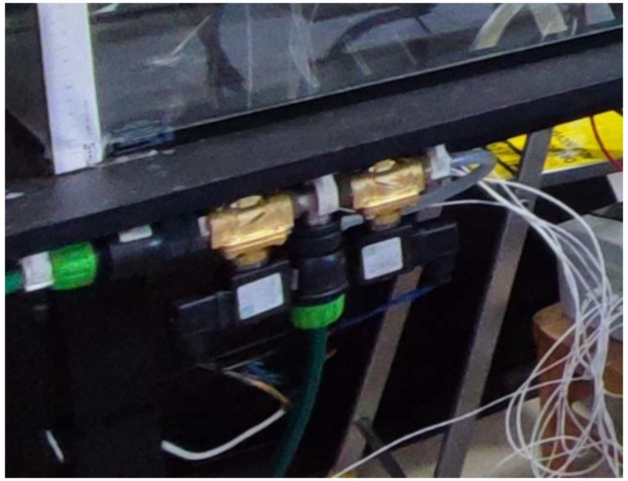
Experimental setup: hydraulic circuit

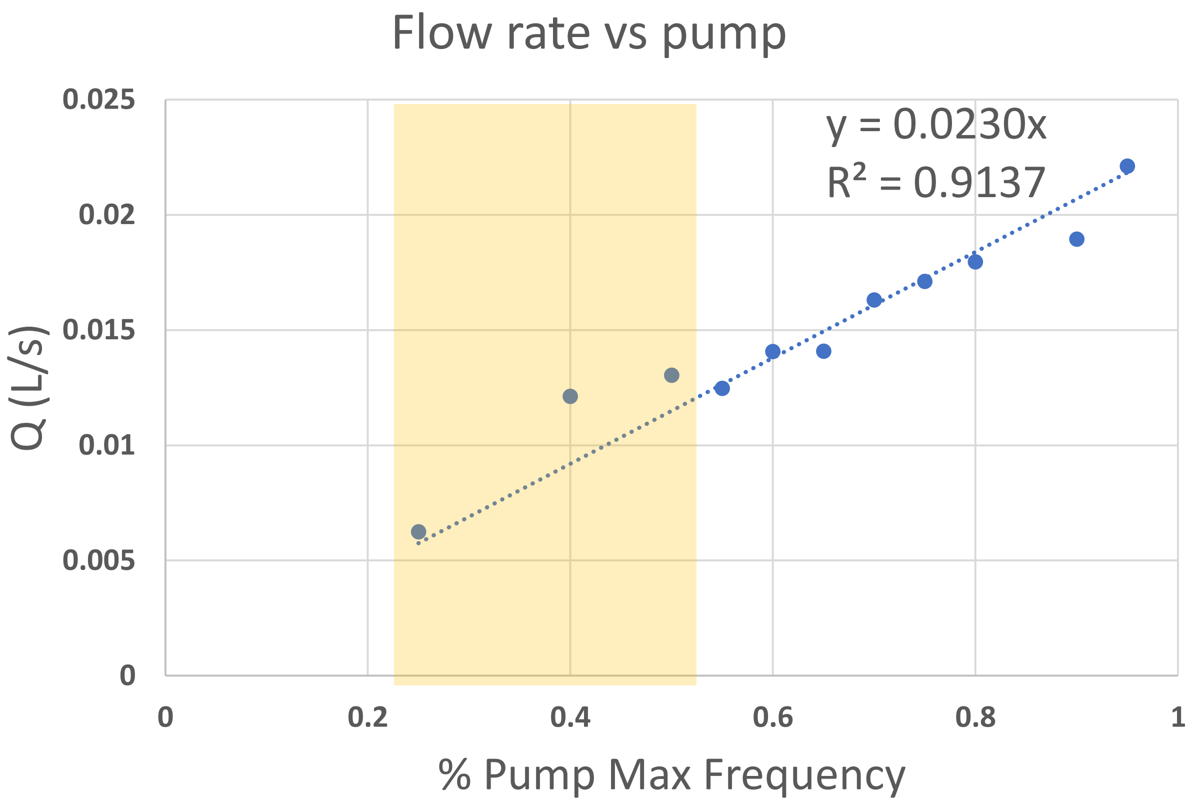
Electrovalves



Pump and flowmeter







Range (L/s)

$6 \times 10^{-3} < Q < 2 \times 10^{-2}$

Experimental setup: temperature measurements

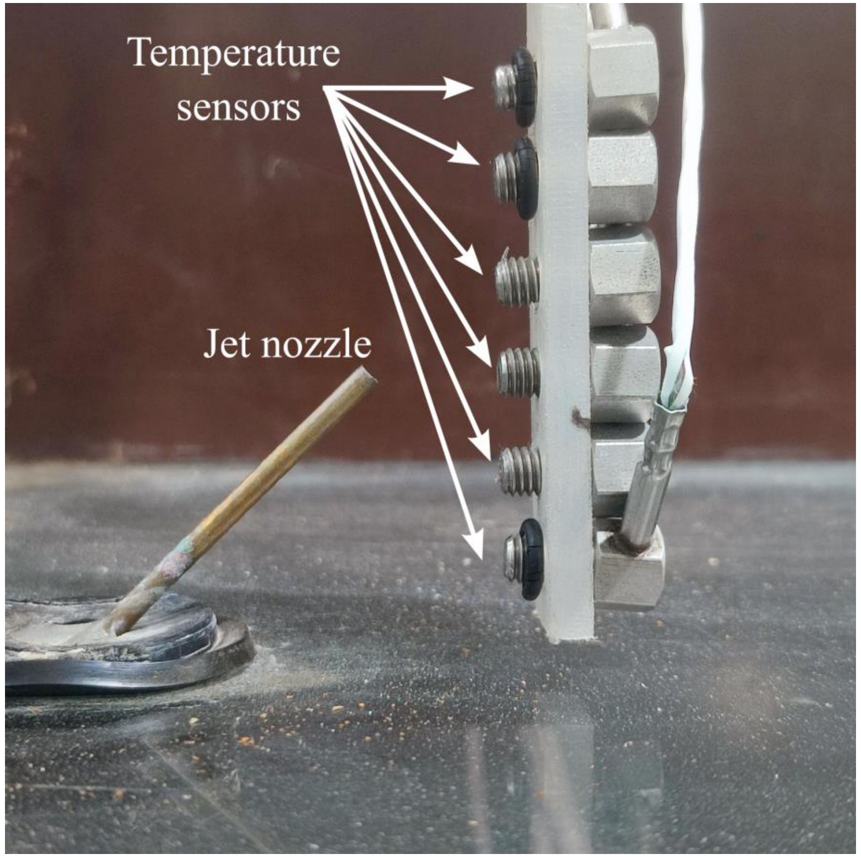
Point wise thermometers:

8 PT100 + acquisition system: 6 for temperature profile measurement,
2 for determining boundary conditions

3 PT100B + controllers: 1 for hot water tank
1 for room temperature
1 for boundary conditions in the tank

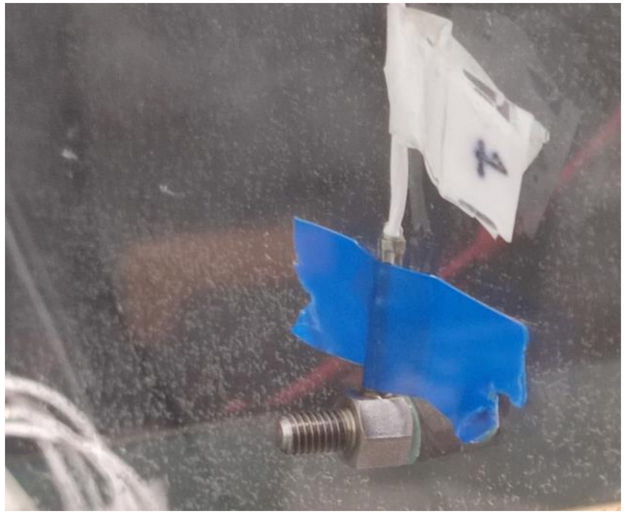
Processing and analysis software in Matlab (developed at IBW PAN)

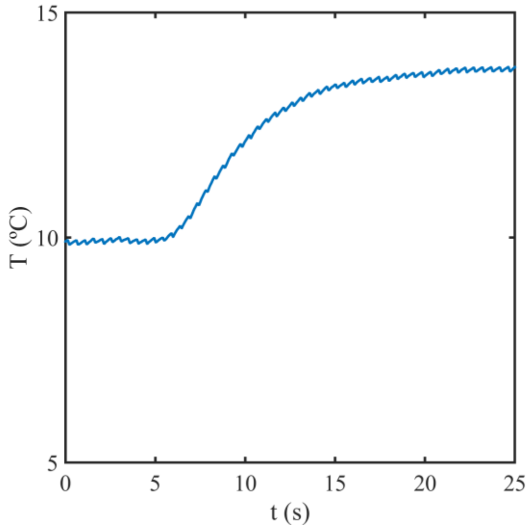
This temperature measuring system was available at IBW PAN from a previous experiment on ice formation



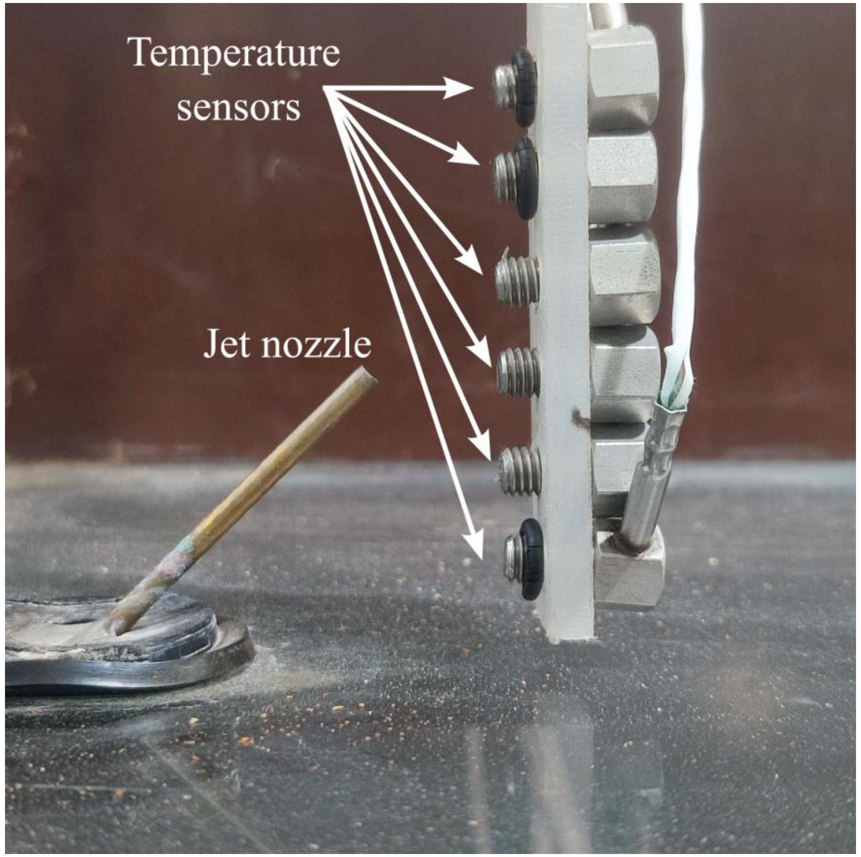
Quite intrusive system!

Experimental setup: temperature measurements





Experimental setup: temperature measurements



Experimental issues:

Quite intrusive system

Only one profile with 6 points is measured at each run.

Time consuming: one run per profile

Impossible to perform temperature and velocity measurements.

Experimental setup: jet trajectory

Cameras:

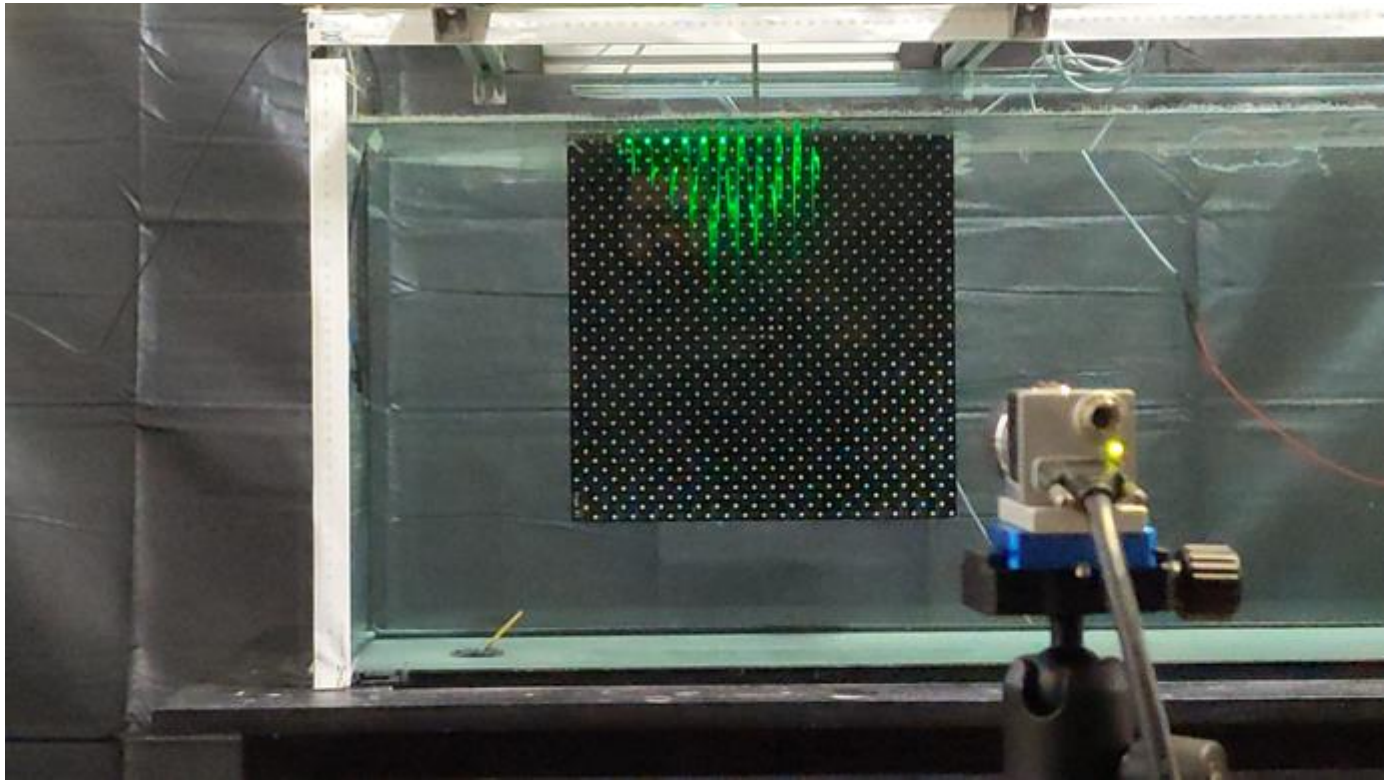
1 cell phone (60 fps)

1 camera Basler 5 Mpix, 120 fps

1 calibration plate

2 laser light sheets (P = 20mW, P=200 mW)

+ image processing tools



Experimental setup: velocimetry

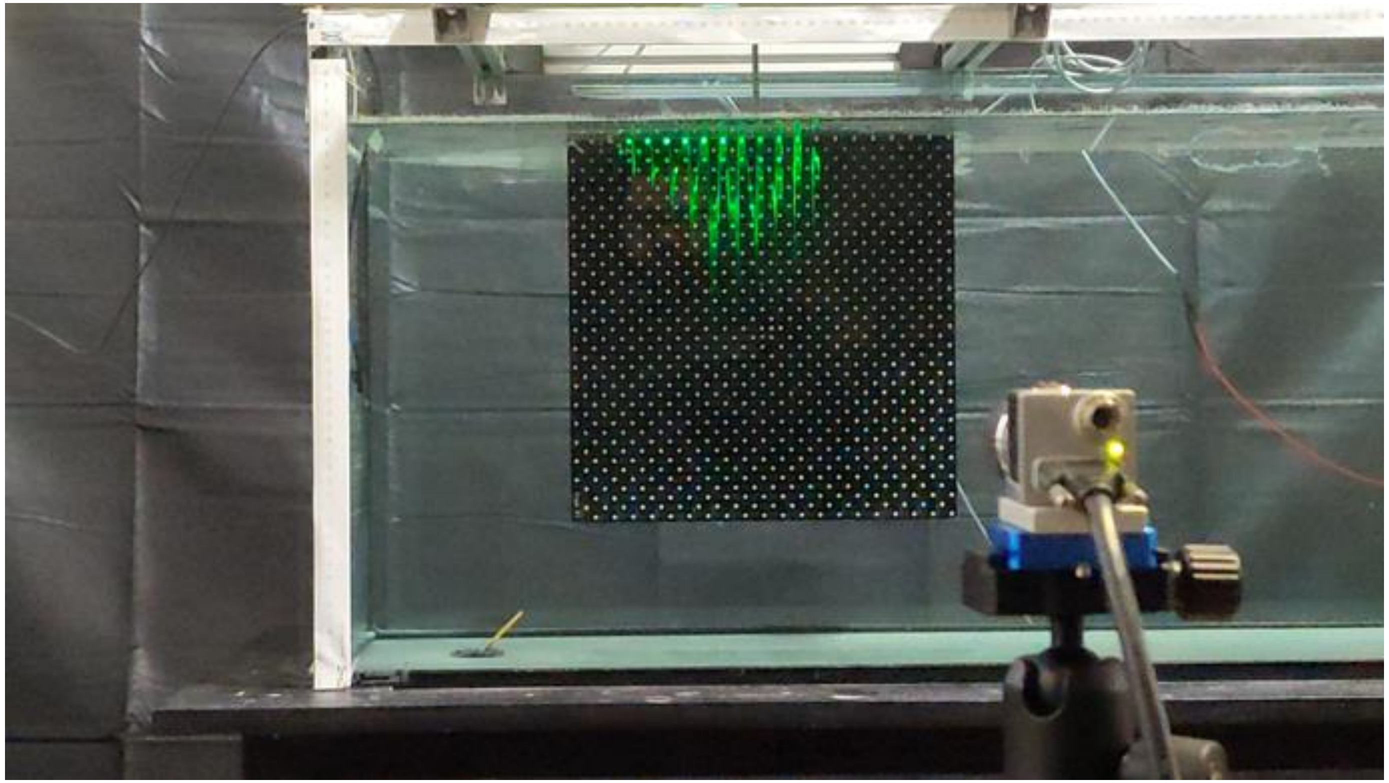
Cameras:

1 camera Basler 5 Mpix, 120 fps

1 laser light sheet (P = 20mW, P=200 mW)

1 calibration plate

Processing by MatPIV 1.7



Experimental setup: summary

Setup:

- Aquarium
- Hydraulic circuit: pump/valves/flow meter
- Temperature controllers
- Electric resistance
- Reservoir
- Raspberry Pico: control and acquisition

Trajectory and Velocimetry:

- 1 camera Basler 5 Mpix, 120 fps
- 2 laser light sheet (P = 20mW, P=200 mW)
- 1 calibration plate
- MatPIV 1.7 (freeware)

Cost ≈ 2000 eur

(camera ≈ 1000 eur; Laser ≈ 500 eur; Materials ≈ 500)

Experimental setup in action

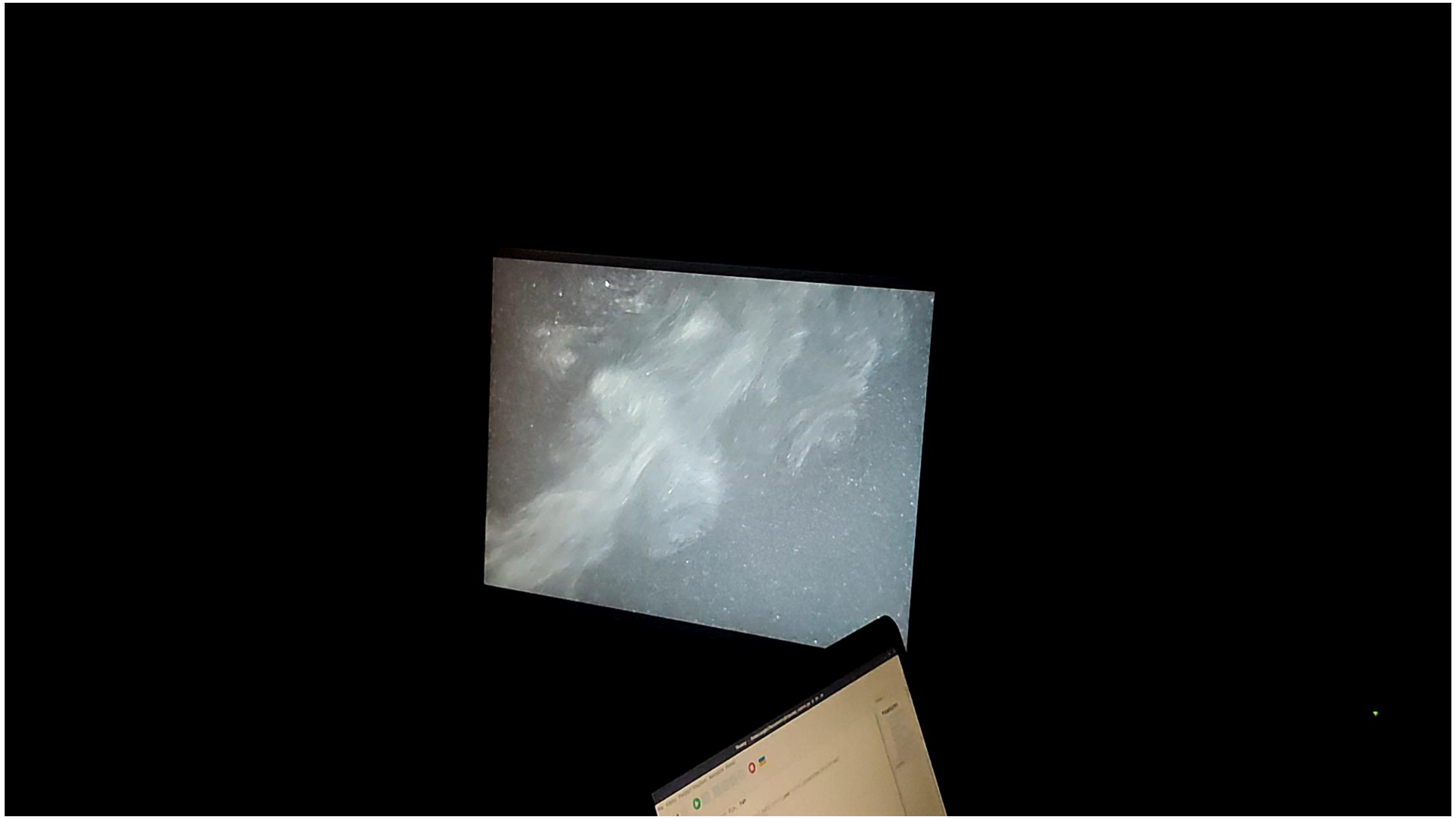
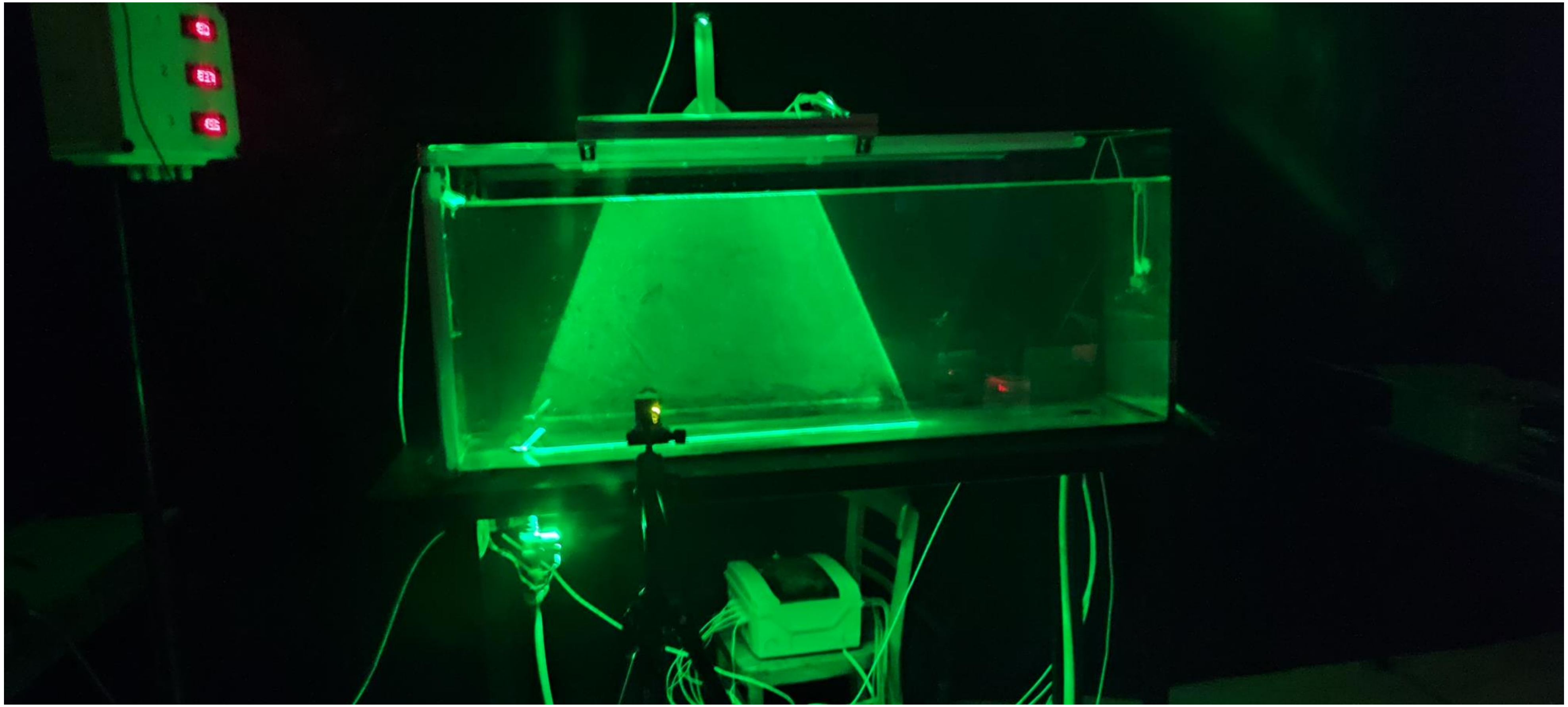


Table 1 Tested condition.

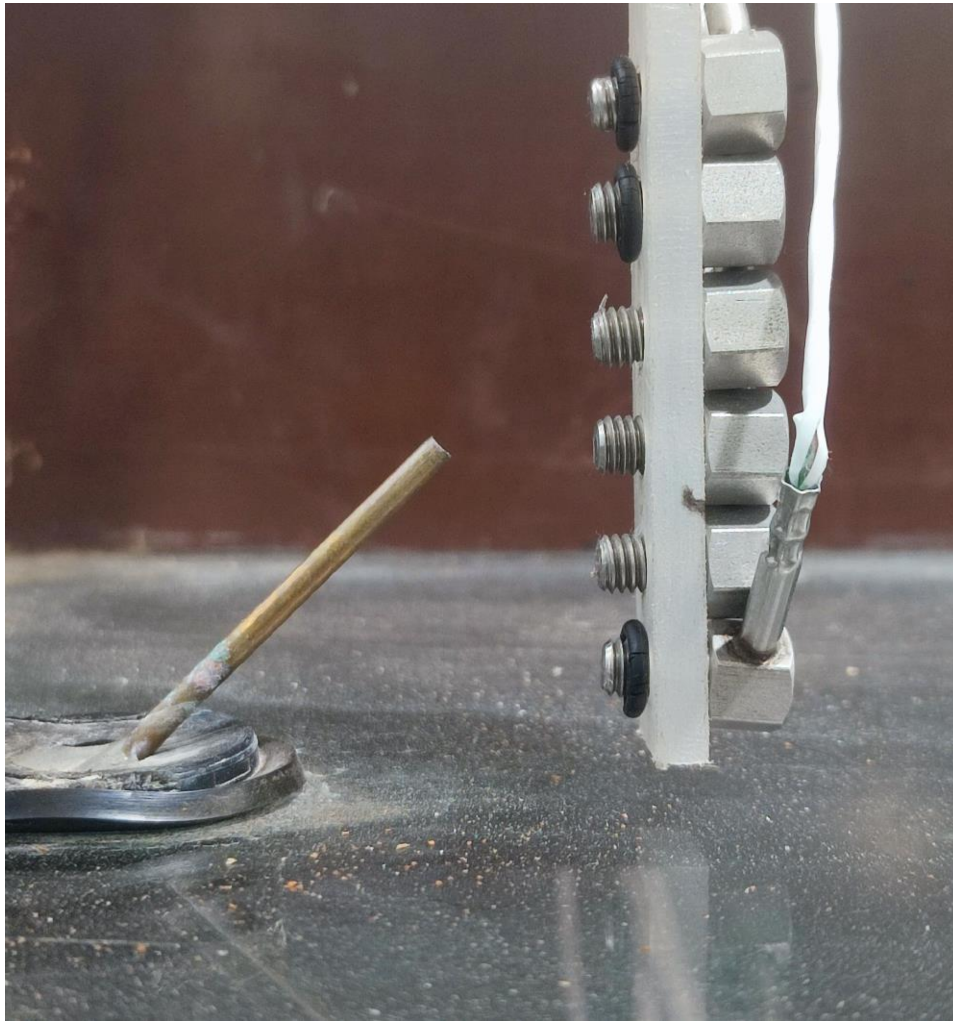
Q (L/s)	d (mm)	Angle (°)	T_{jet} (°C)	T_a (°C)	Re
0.0115	1	45	20	10	3.62×10^3

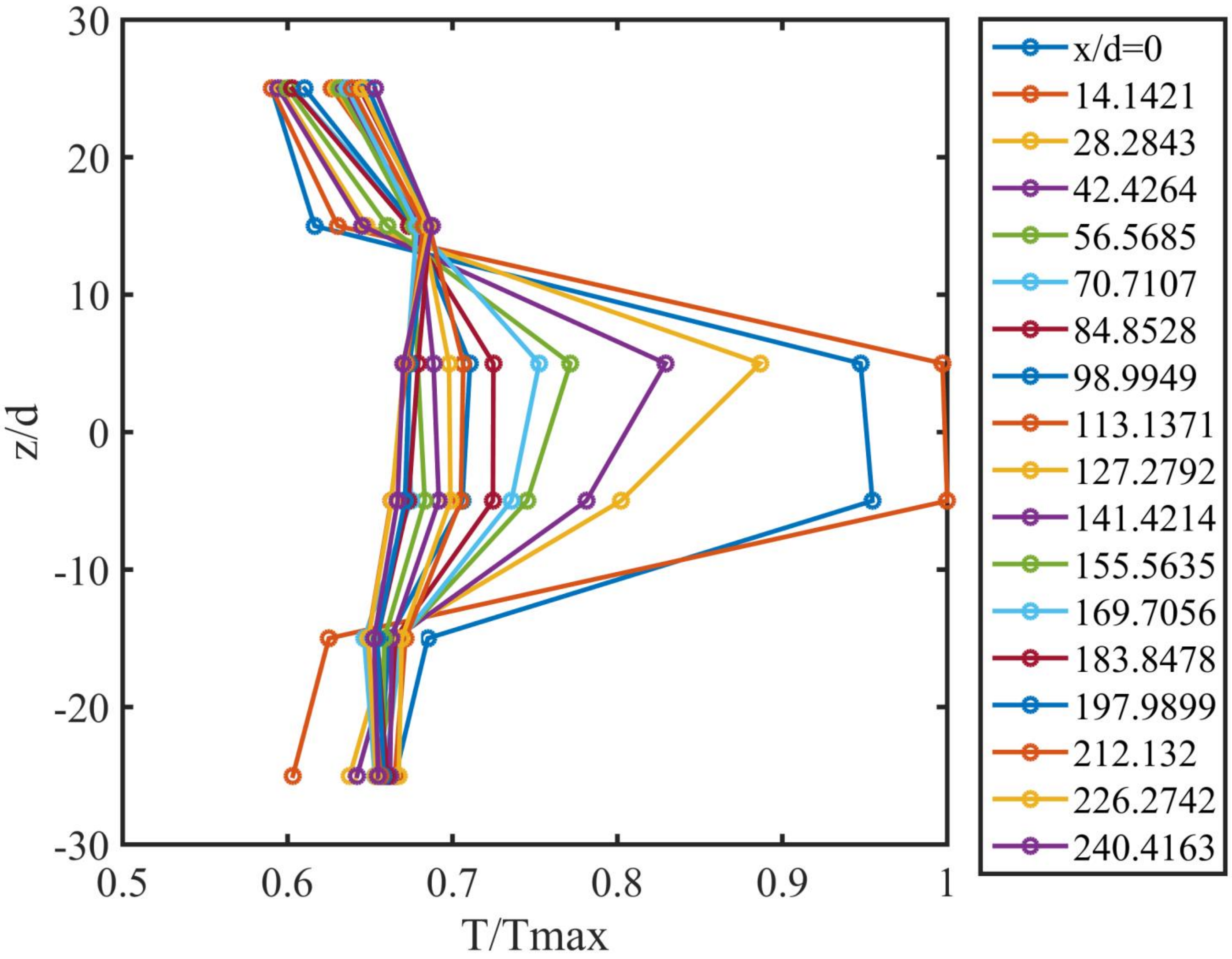
$\ell_M = 0.78$ m

Experimental setup in action



Results: jet temperature





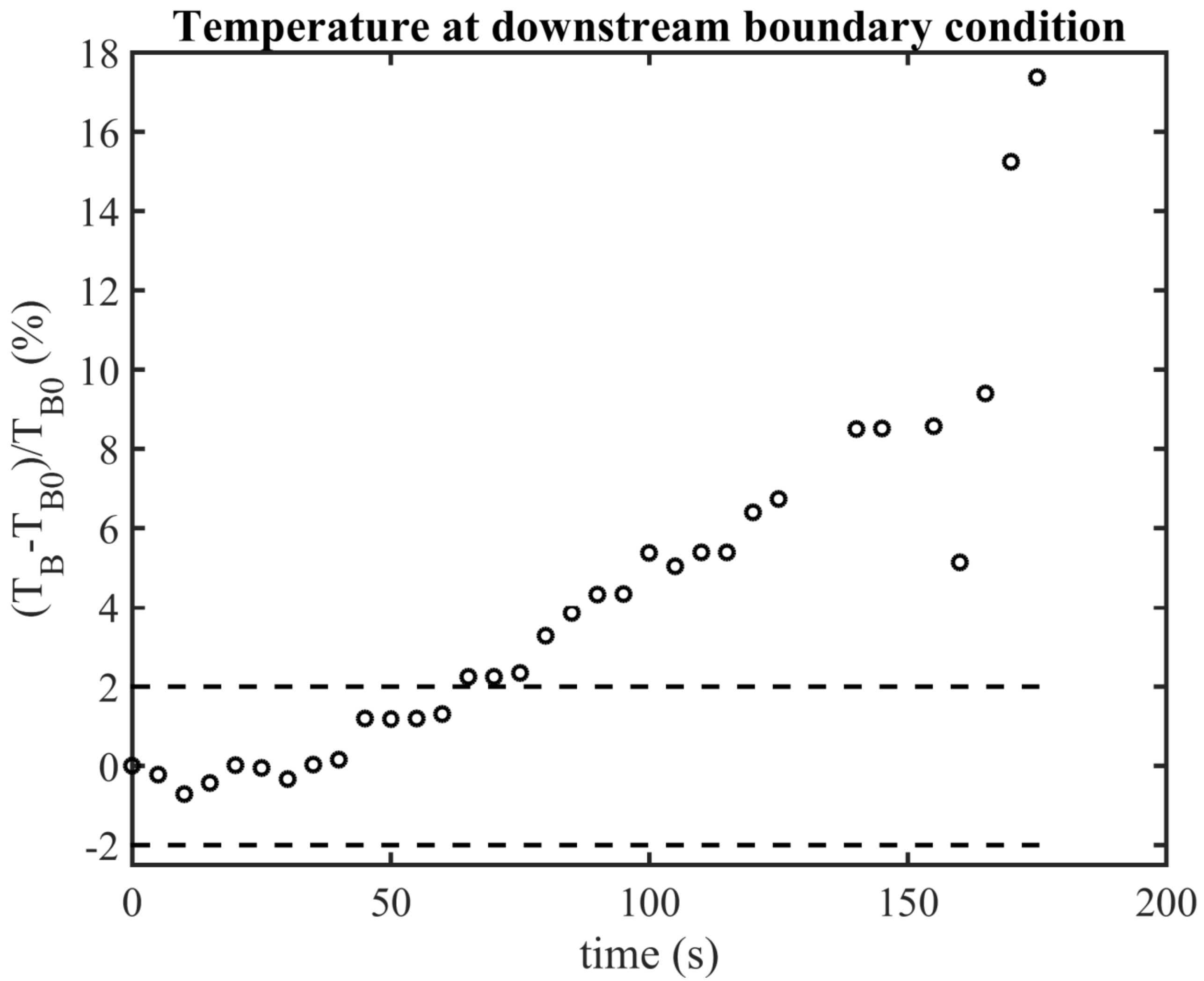
Results: jet temperature

Limitations:

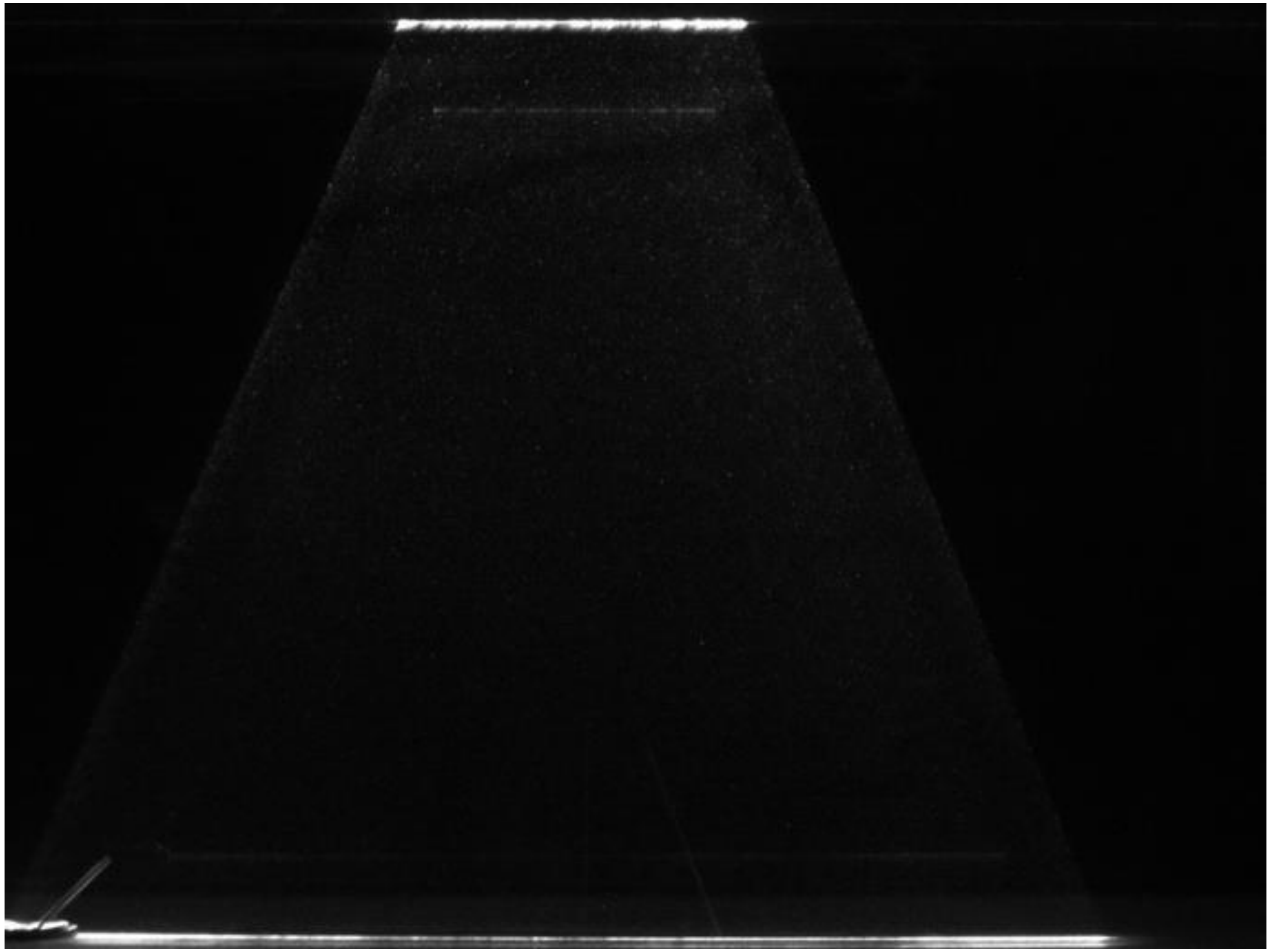
Temperature change at the downstream boundary condition

Run time = 60 s

Number of images: 2400 frames (@ 40 fps)



Results: jet trajectory



Images acquired at 40 fps

Results: jet trajectory

Data processing:

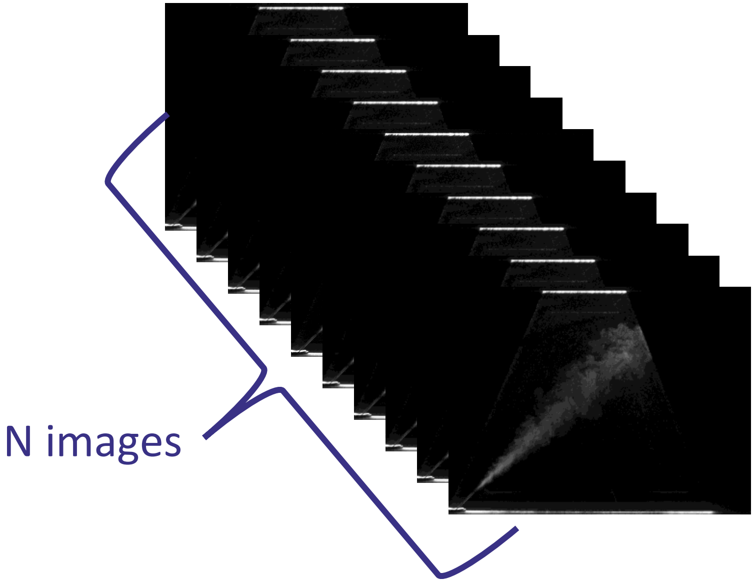
Hot water seeded with TiO_2 (for velocity measurements)

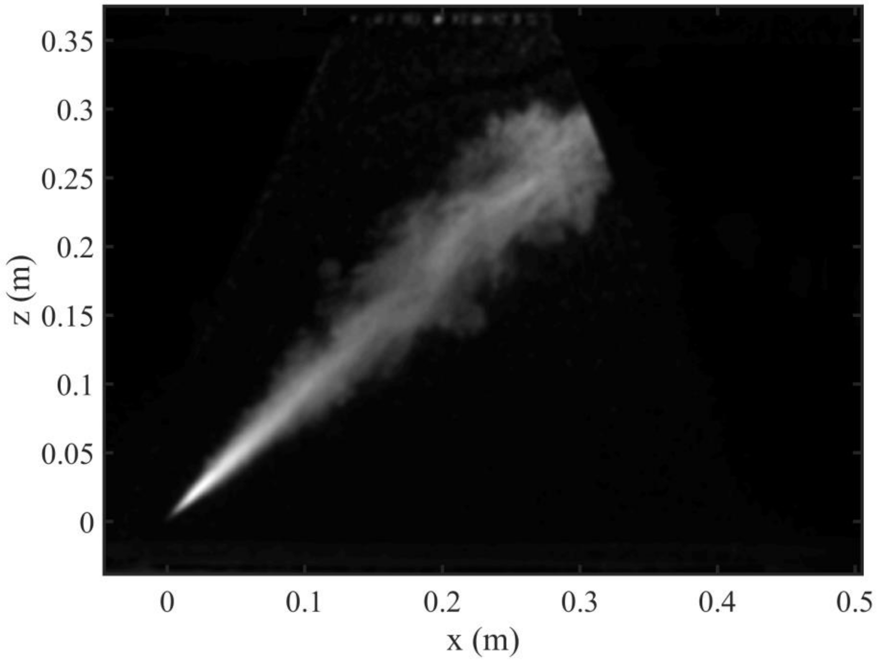
Consider a time interval Δt (0.25 s, N = 10 images)

Remove the background

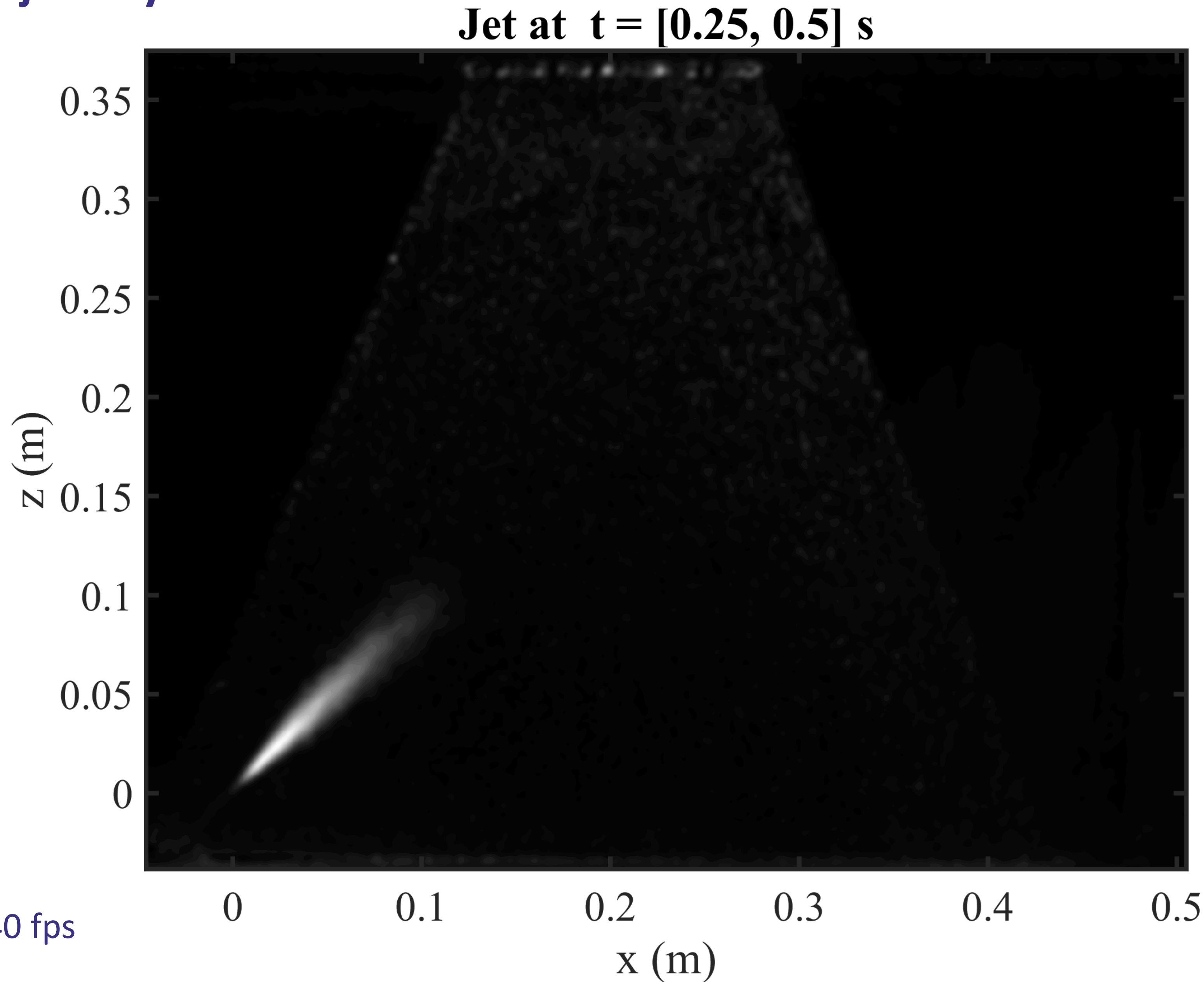
Average images in Δt

Process images: Gaussian smoothing and threshold analysis



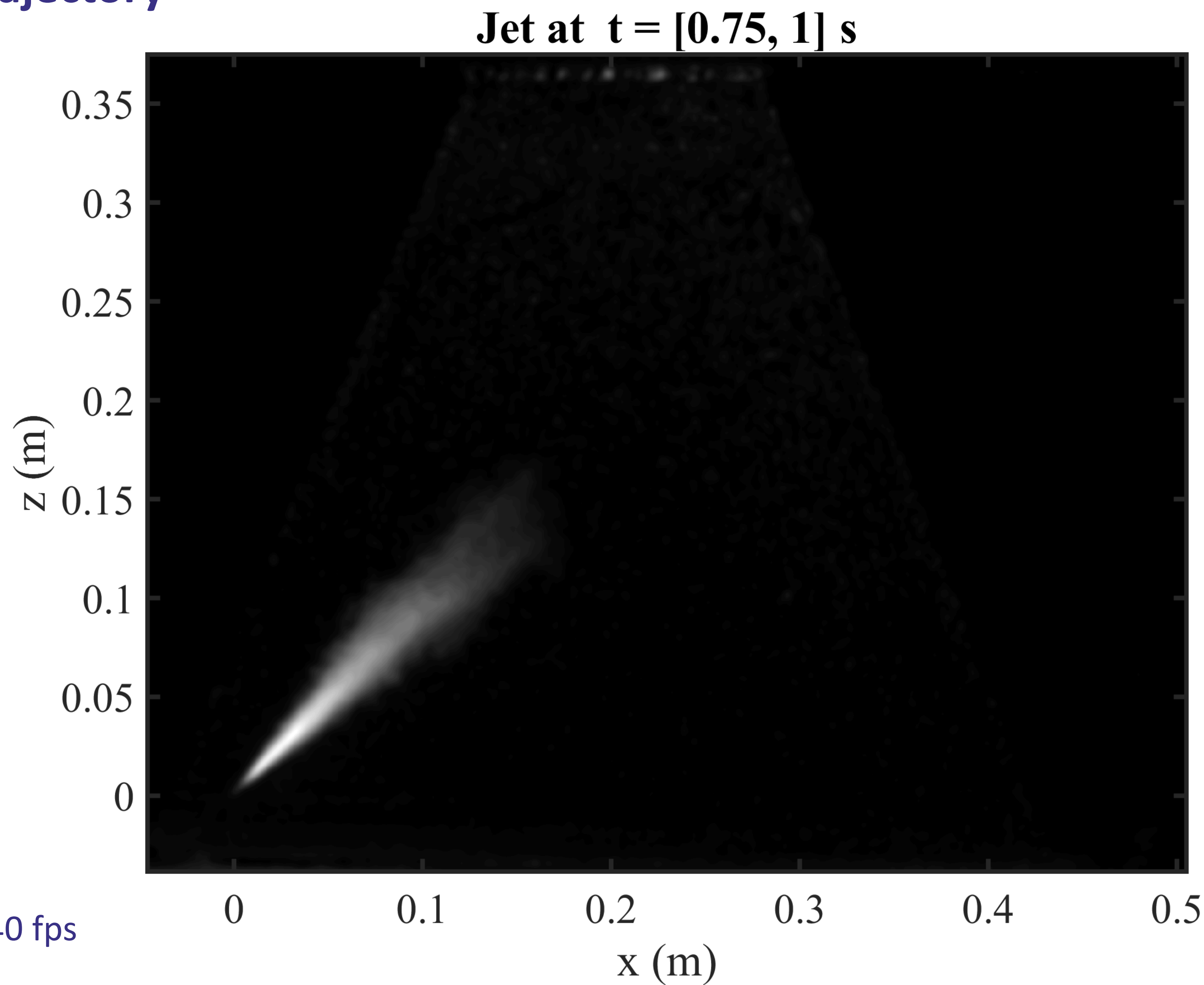


Results: jet trajectory



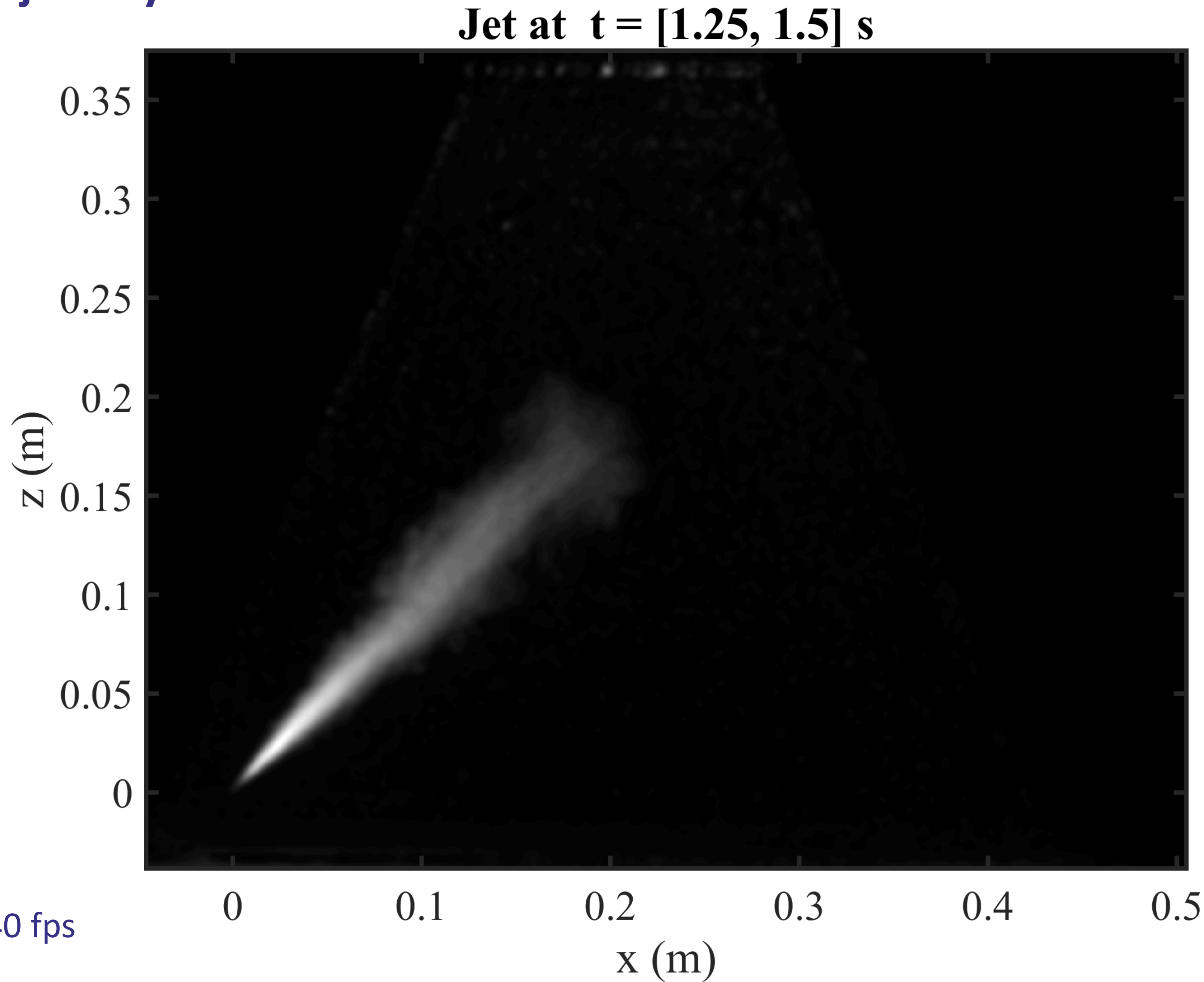
Images acquired at 40 fps

Results: jet trajectory



Images acquired at 40 fps

Results: jet trajectory



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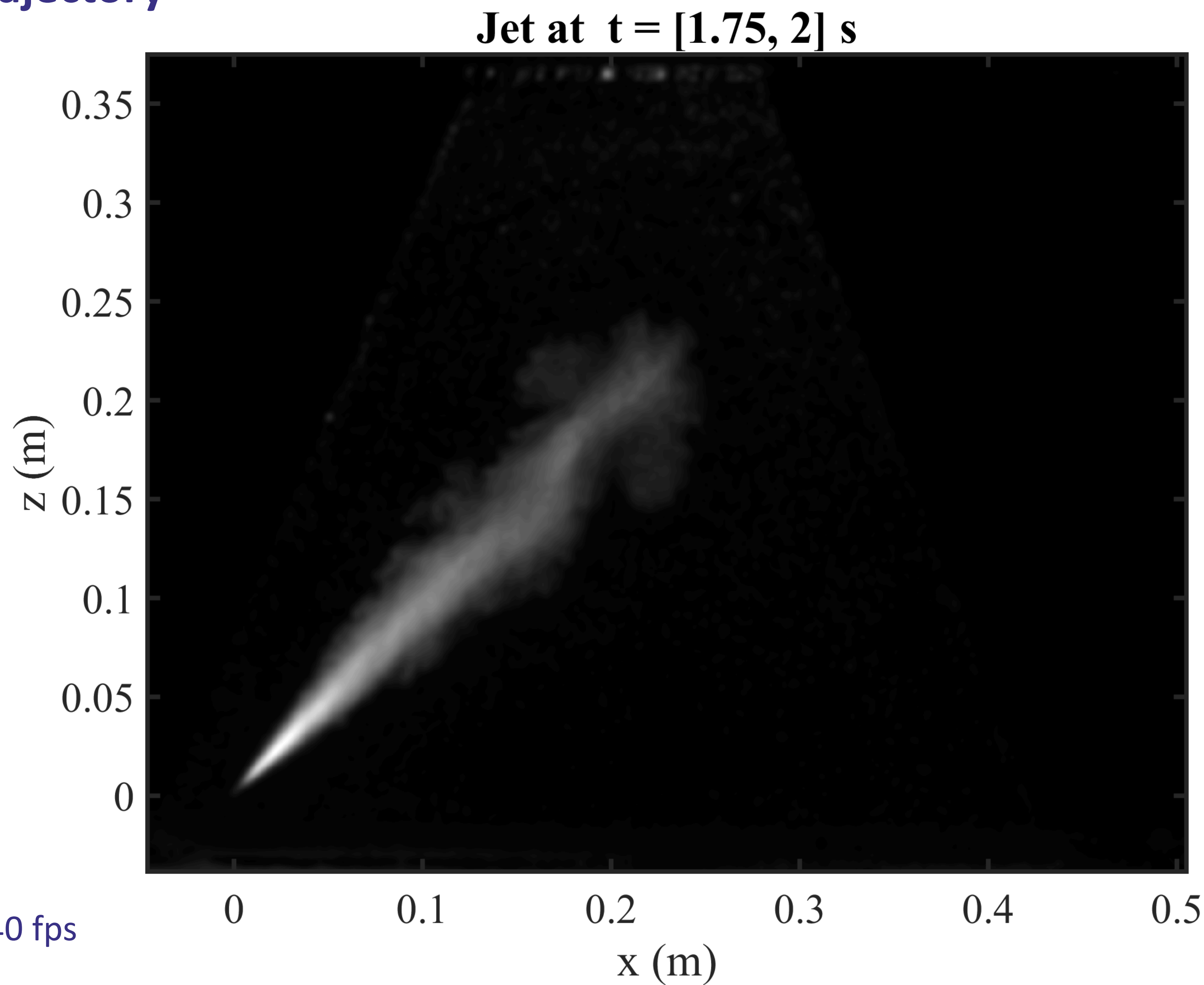

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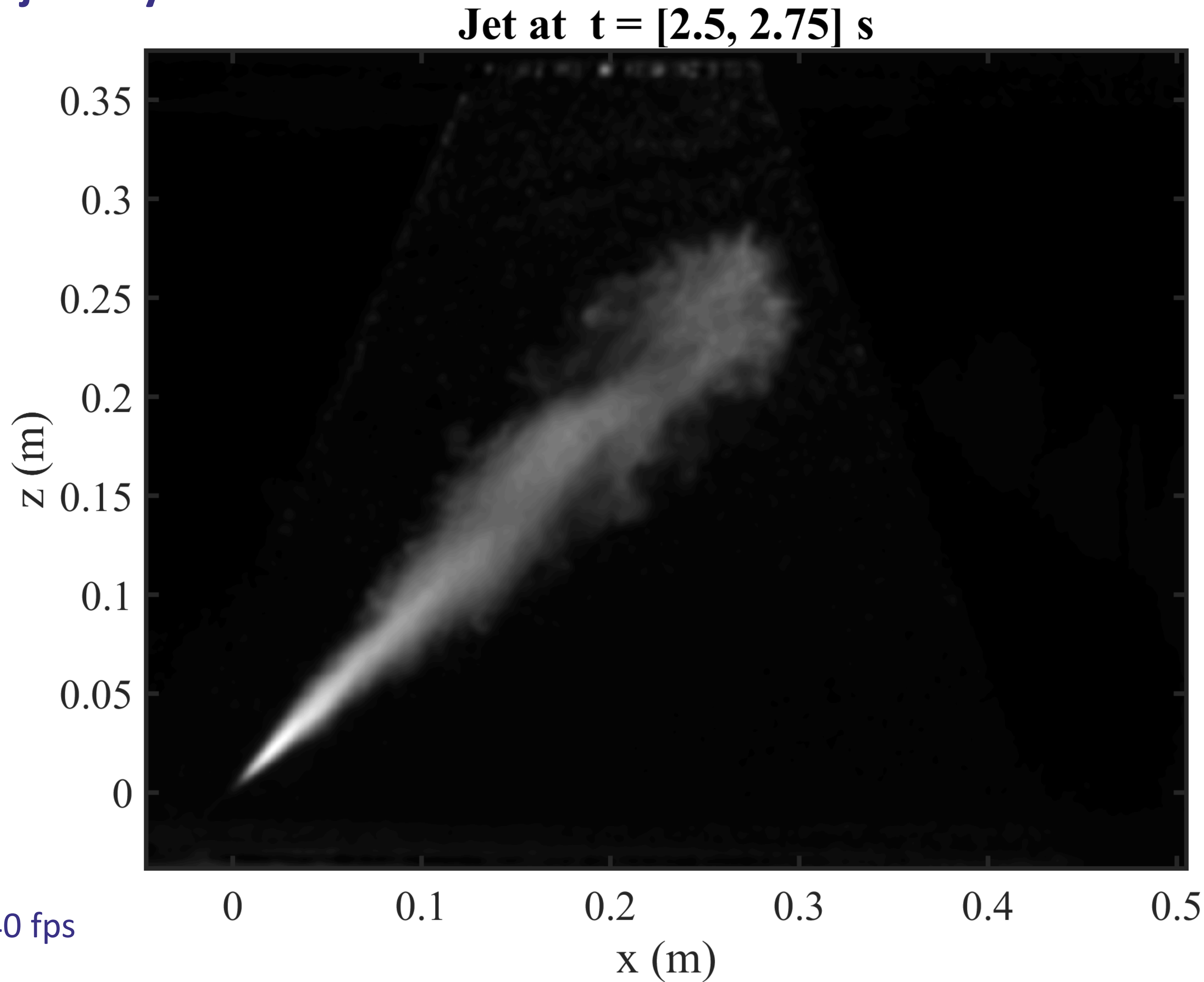

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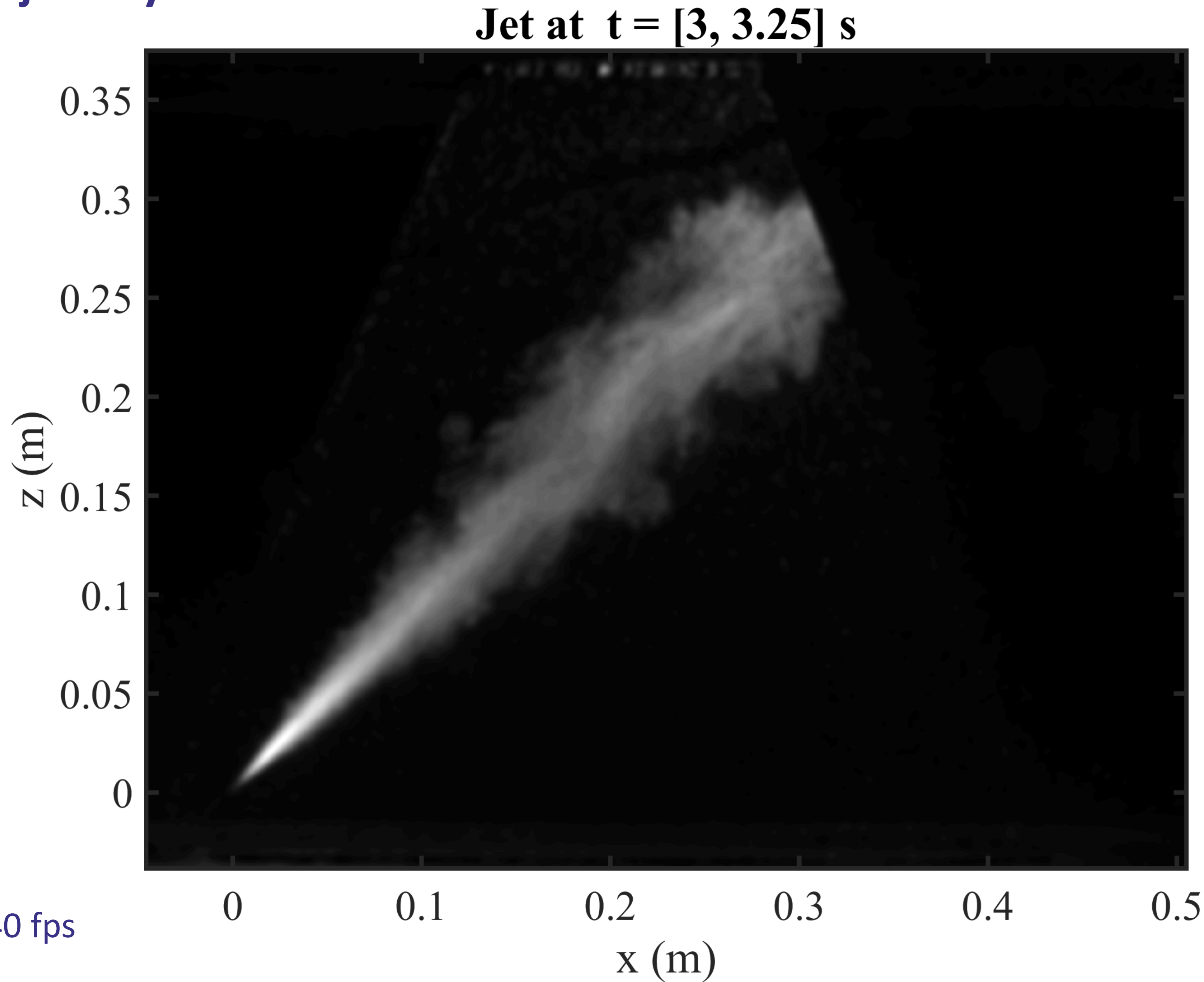
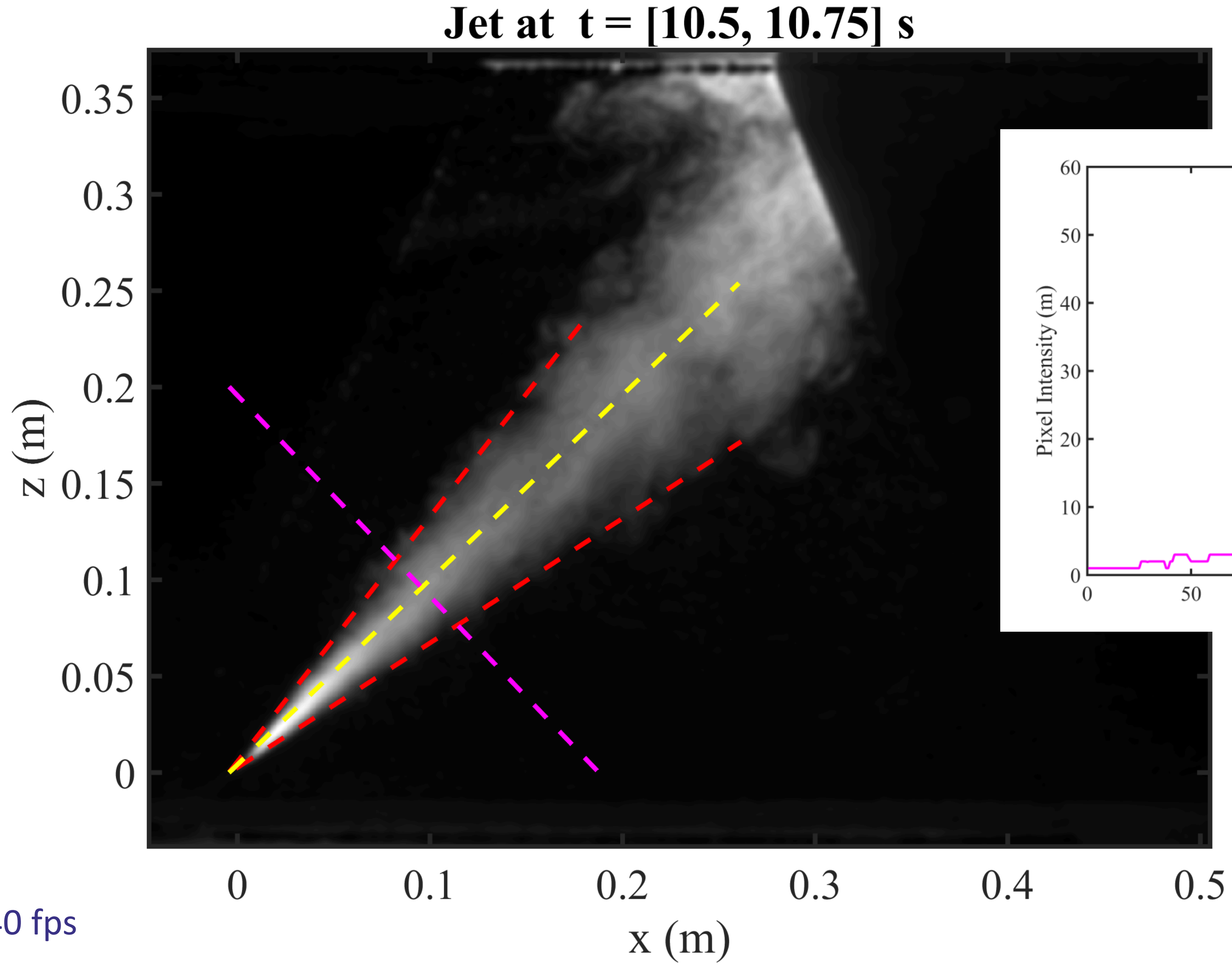
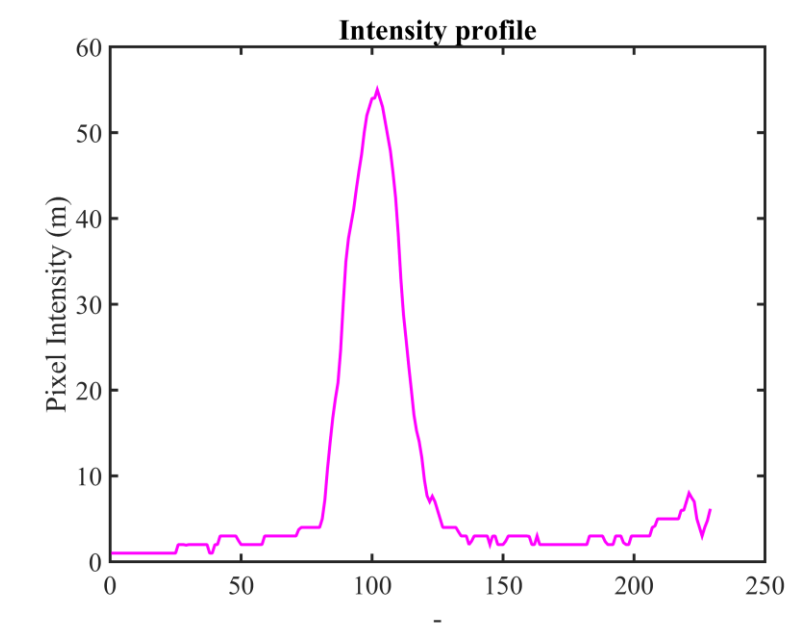


Images acquired at 40 fps

Results: jet trajectory





Using intensity profile to compute jet parameters?

Images acquired at 40 fps

Results: jet velocity

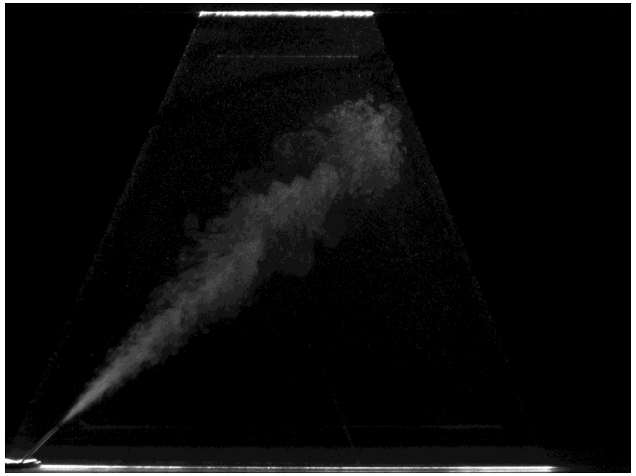
Data processing:

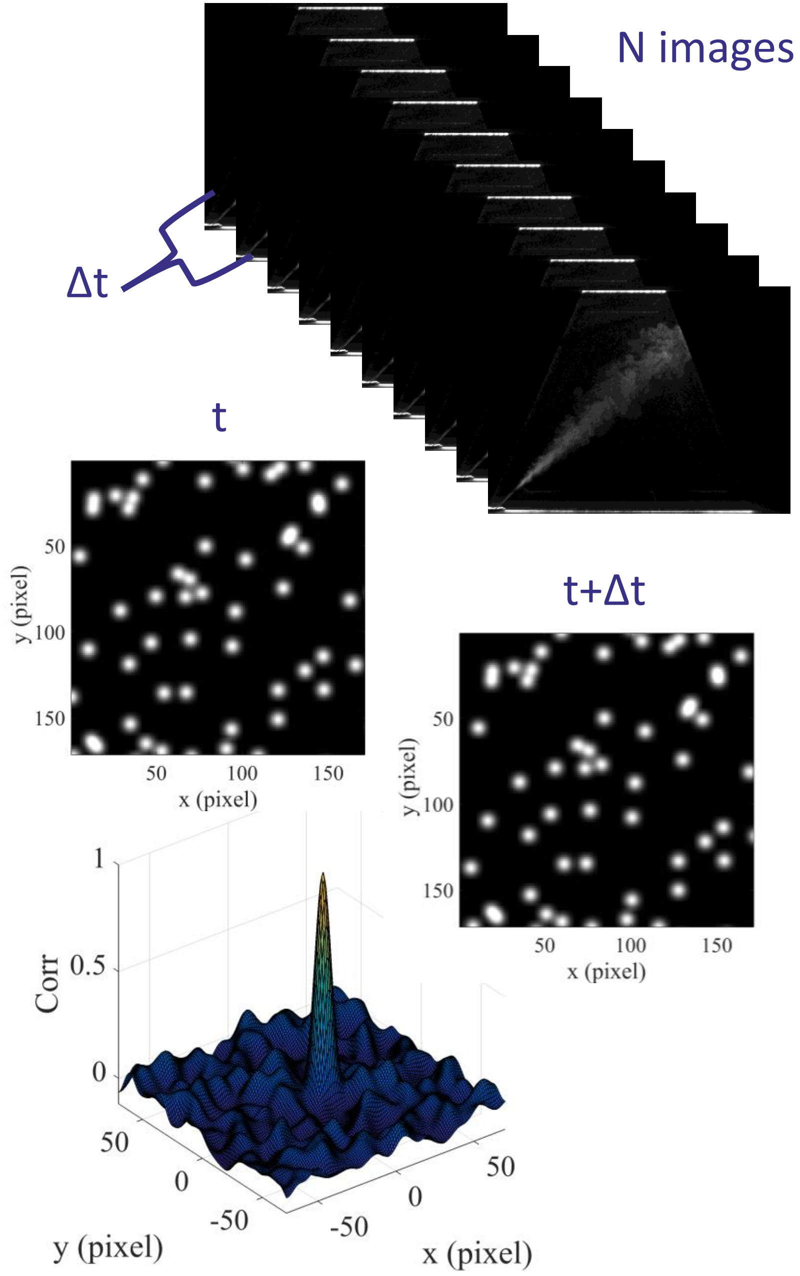
Hot water seeded with TiO_2 (for verlocity measurements)

Consider each pair of images: N images = (N-1) velocity fields

Remove the background

Time Resolved Particle Image Velocimetry (MatPIV 1.7)





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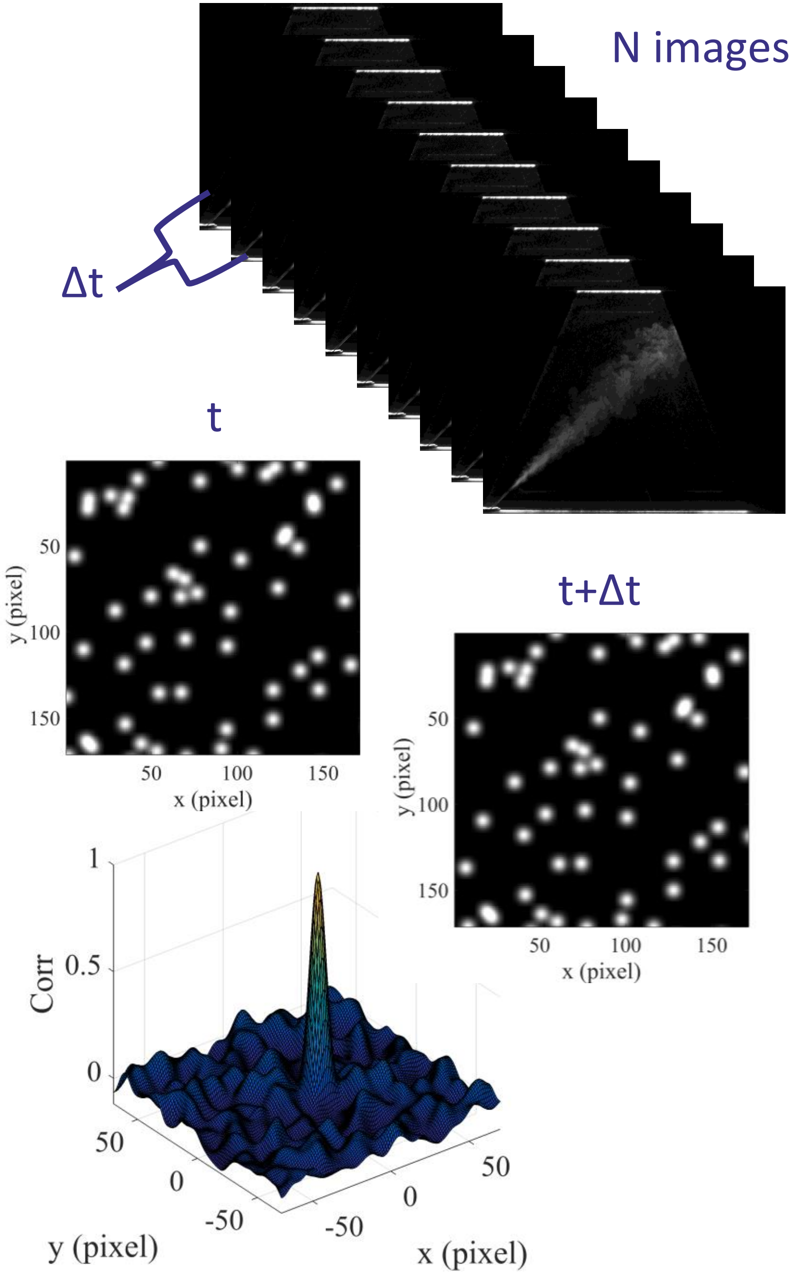
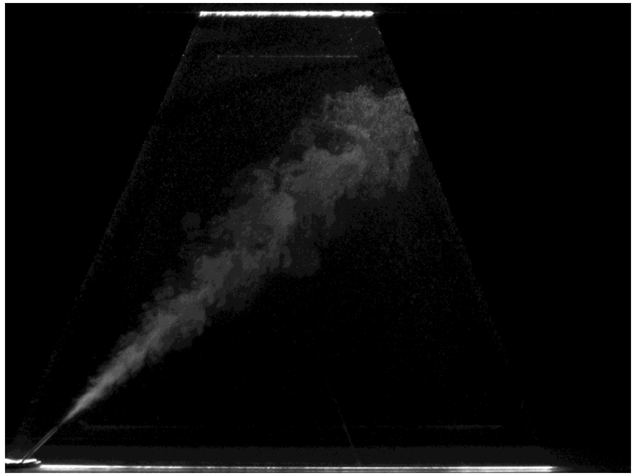




Come learn about PIV in the W.A.T.E.R.Summer School

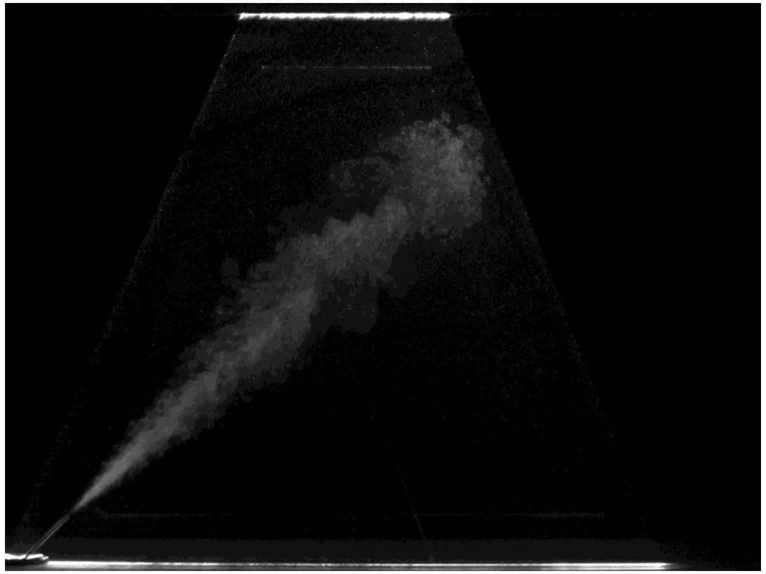
Results: jet velocity

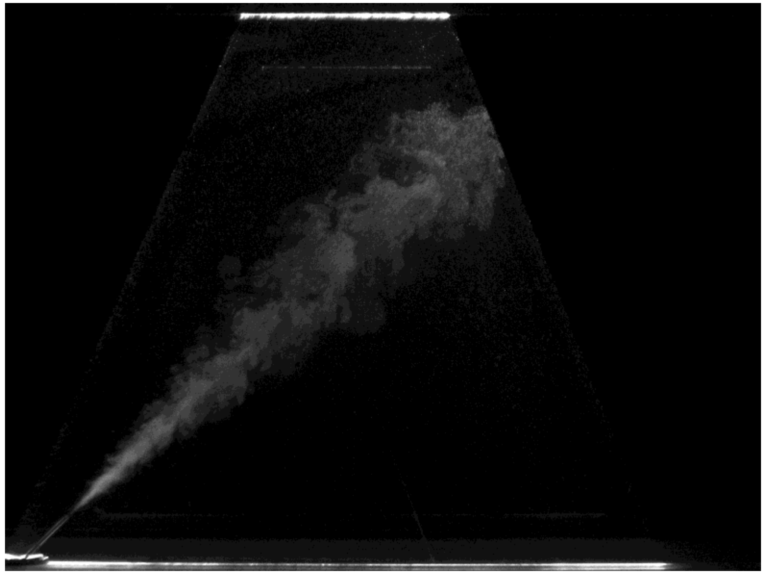
PIV processing:

256 x 256 to 32 x 32 with 50% overlap

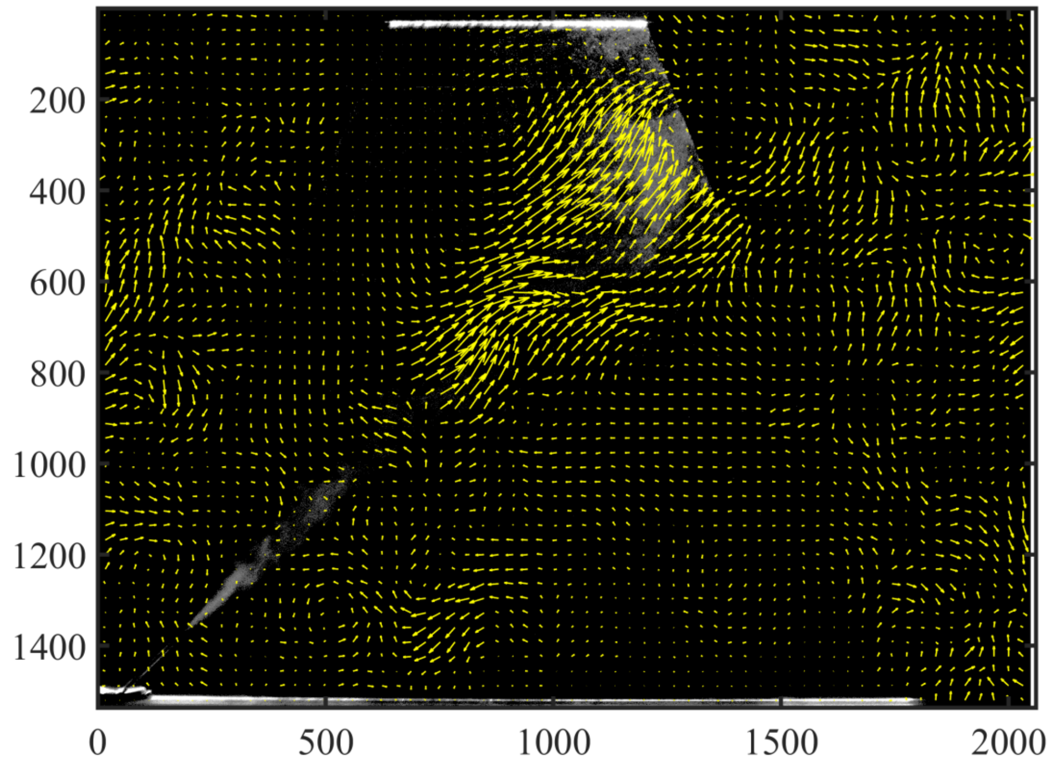
201 frames processed

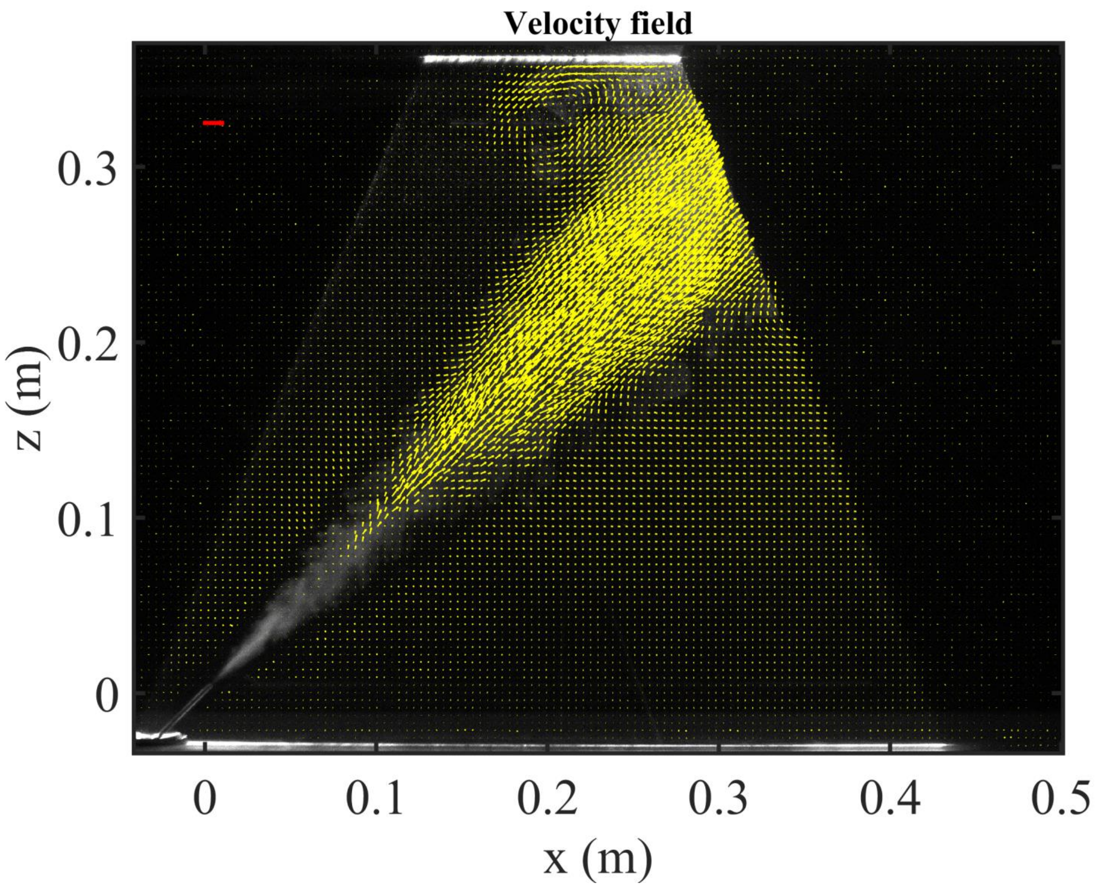
200 velocity fields





Results: jet velocity





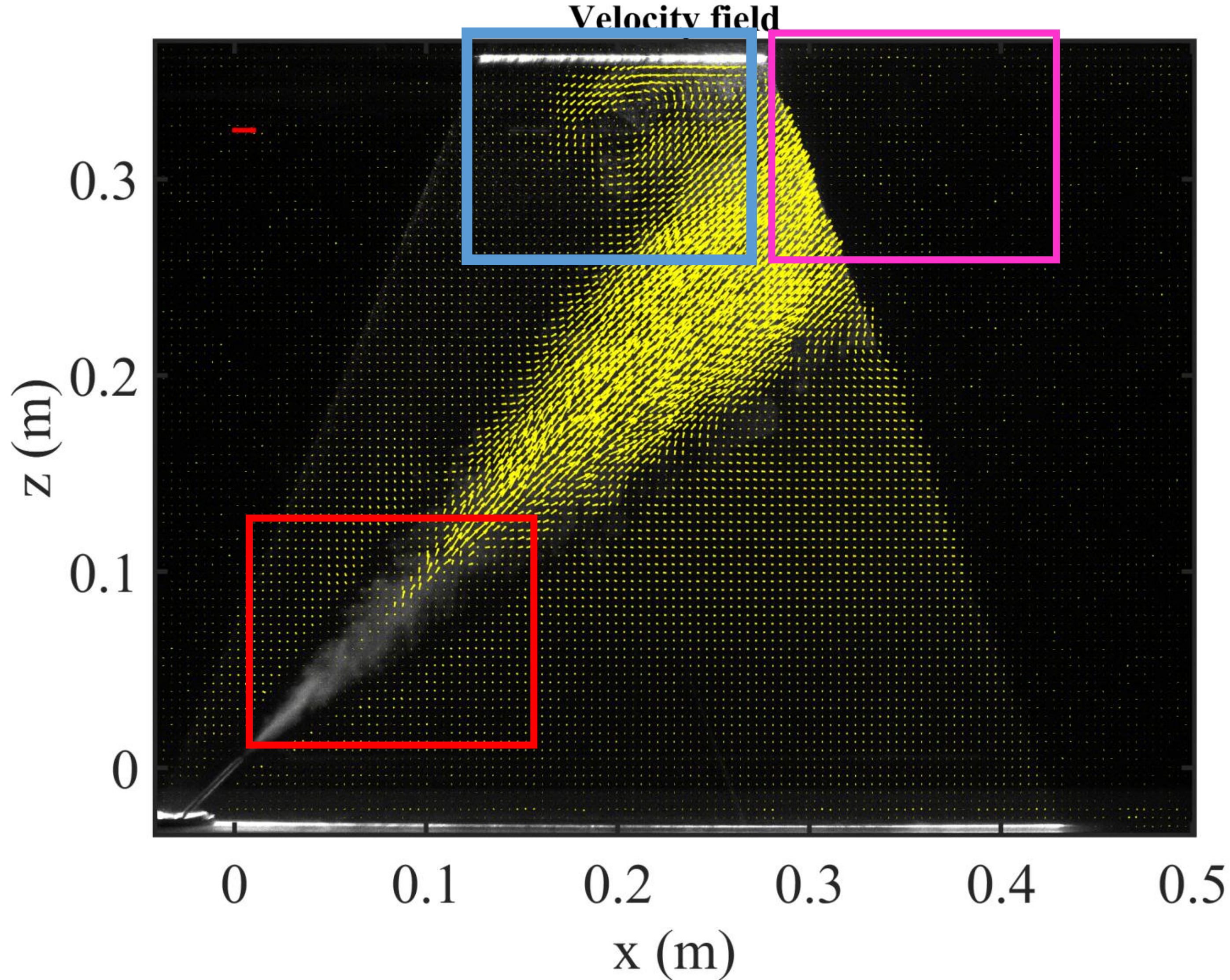
Results: jet velocity

Issues

Near-field is not properly resolved (no spatial resolution)

Trapezoidal laser light sheet placed above the channel

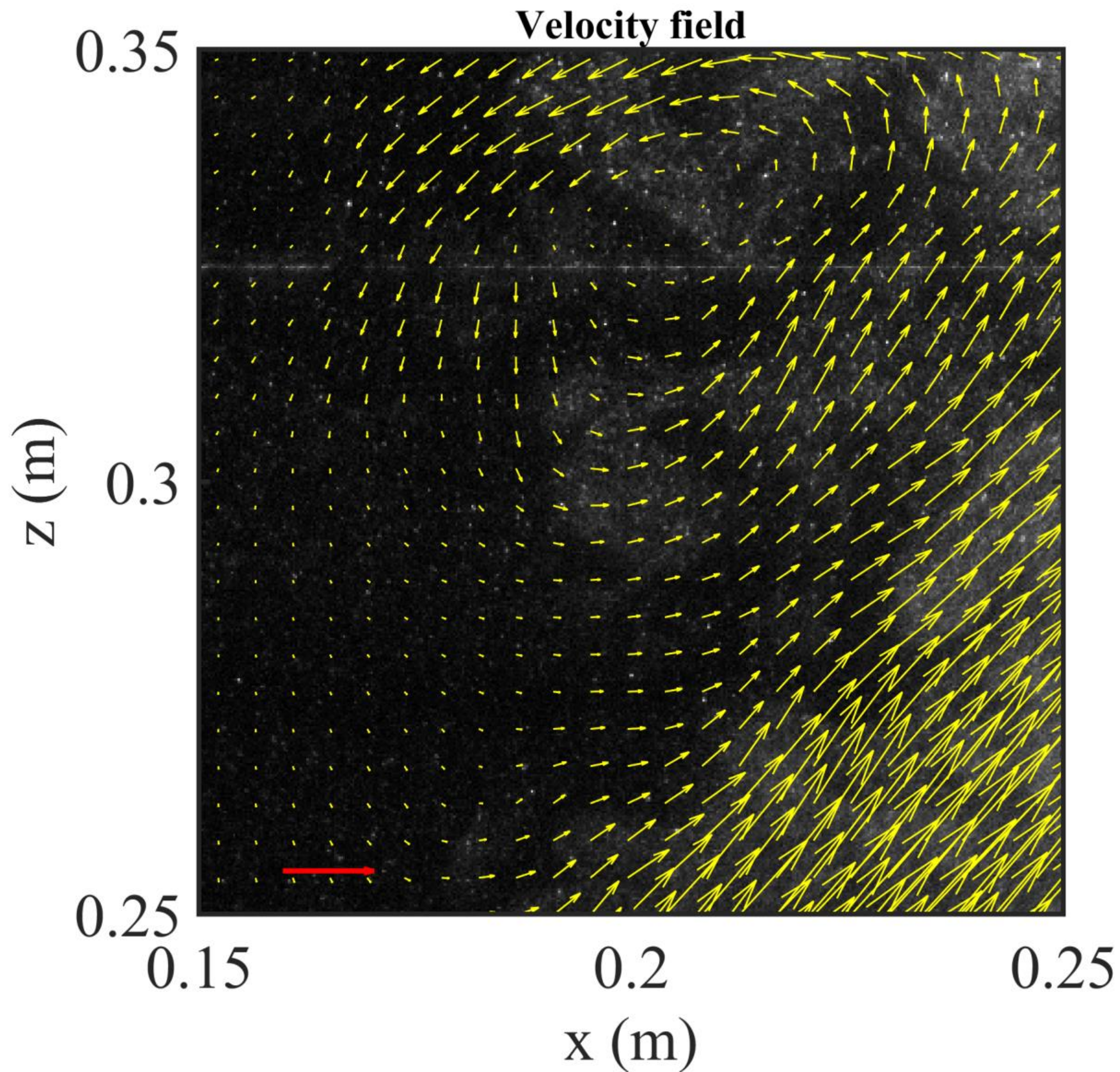
Far-field: well resolved and part of the interaction with the free surface



Results: jet velocity

Interaction between jet and free surface

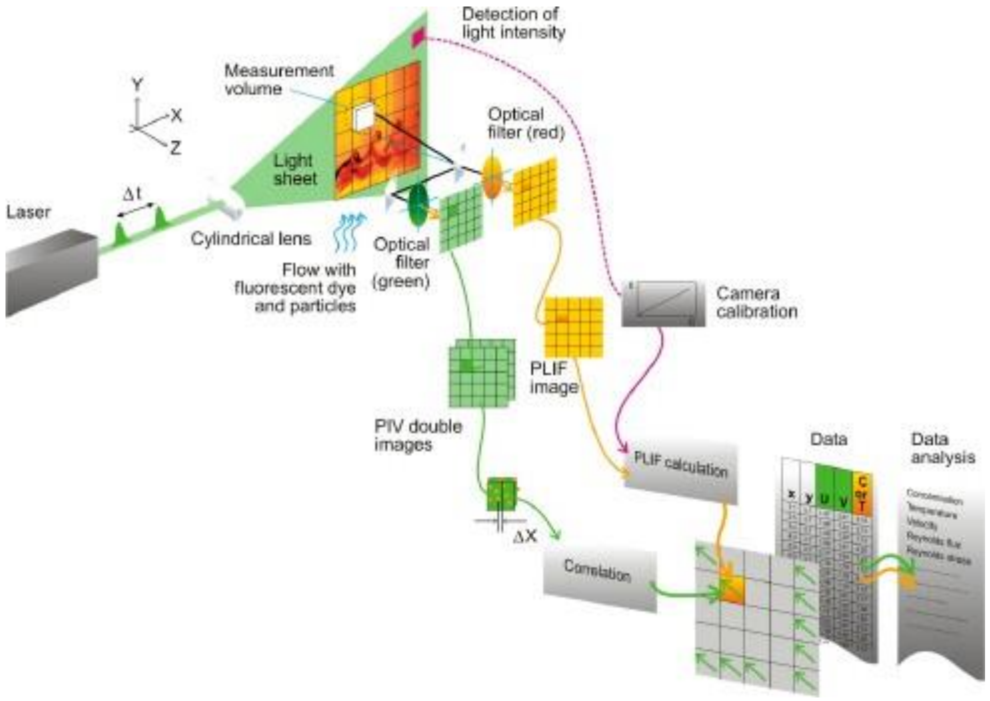
Results so far are promising, but there's still room for improvements

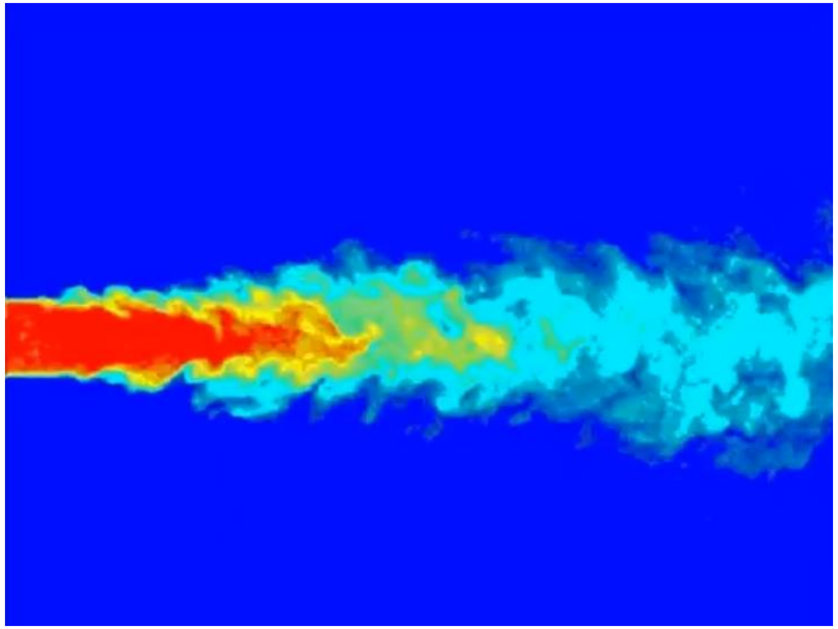


Future work

Address the weakest point: temperature measurements

Laser Induced Fluorescency (LIF)
Measure velocity and temperature at the same time





https://www.dantecdynamics.com/solutions/fluid-mechanics/laser-induced-fluorescence/measurement-principles-of-planar-lif/

Future work

Tests in a larger water tank

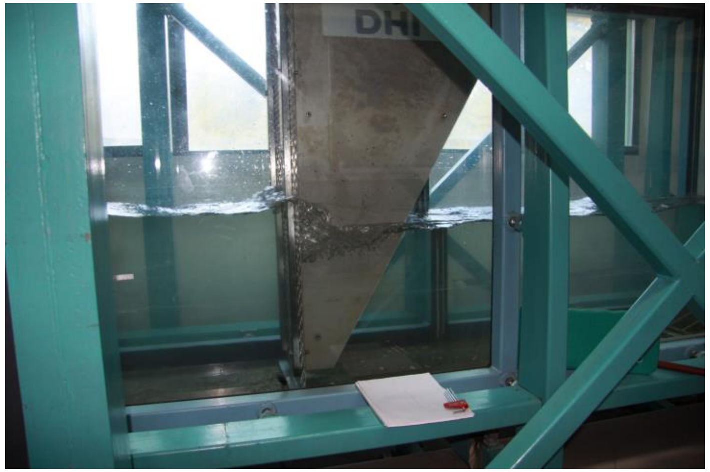
Increase the range of jet's Reynolds numbers

Less influence from the boundaries

Tests in the wave-flume

New set of experiments with thermal jets to be made in the wave flume

a) length = 64 m; b) width = 0.6 m; c) height=1.4 m (operational h up to 0.8 m);



Conclusion

- An experimental setup to measure termal jets was presented.
- The termal jet setup is working and *continuously* being improved.
- Planar jet trajectory and planar jet velocity field can be measured by means of imaging techniques (non-intrusive).
- Temperature measurements with PT100 thermometers are quite intrusive, and time consuming.
- Temperature profiles are limited by the number of sensors
- For now temperature profiles and velocity measurements have to be made separately.

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Thank you for your attention.

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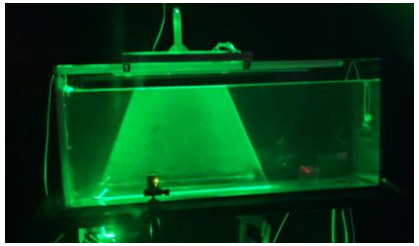

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