R+D Project Study on the Brine Dilution Process

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1. Problem Scope

- Management model for desalination plants.
- Advanced dilution system in the *near field*: optimal performance, minimized environmental effects.
- Numerical simulation of *far field*: waste discharge scenarios.
- Main interest on experimental aspects:
  - ✓ Kinematics in the *near field* domain: z_{max}/D.
  - ✓ Conditions for transition to the *far field* domain: distances $x \gtrsim 10D$.

2. Objectives

- Experimental study on the *near field* under project design settings.
- Governing variables inside the transition *near field–far field* region.
- Input data for the *far field* simulation model: validation.

3. Theoretical Background

- Jet integral model, Jirka (2004) → volume, momentum and buoyancy fluxes:

$$\begin{cases} Q_0 \sim D^2 U_0 \\ M_0 \sim D^2 U_0^2 \\ B_0 \sim g' D^2 U_0 \end{cases}$$

- Kinematical and geometrical description → maximum jet elevation as a functional dependence on D, F_d, H, ρ_0, ρ_a:

$$\frac{z_{max}}{D} = \mathfrak{F}\left(F_d, \frac{\rho_0}{\rho_a}, \frac{H}{D}\right)$$

- Jet–plume flow regime → densimetric Froude number F_d:

$$F_d = \frac{U_0}{\sqrt{g'D}} = \frac{U_0}{\left[g\left(\frac{\rho_0 - \rho_a}{\rho_a}\right)D\right]^{1/2}}$$

- g' → Boussinesq approximation, Roberts *et al.* (1997) → buoyancy represented by modified gravity if density changes are much smaller than local density:

$$\frac{\rho_{local} - \rho_a}{\rho_a} << 1$$

- Jet-ambient mixing → maximum dilution in the impact point.
- Motion across the *far field* domain: advection, turbulence, buoyancy and pressure gradient, Ellison & Turner (1959), Horsch (2004).
- Simplificaciones:

$$\begin{cases} \frac{H}{D} >> 1 \;\Rightarrow\; \text{const.} \\ \frac{\rho_0}{\rho_a} \simeq \text{const.} \end{cases} \Rightarrow \frac{z_{max}}{D} = \mathfrak{F}\left(F_d\right)$$

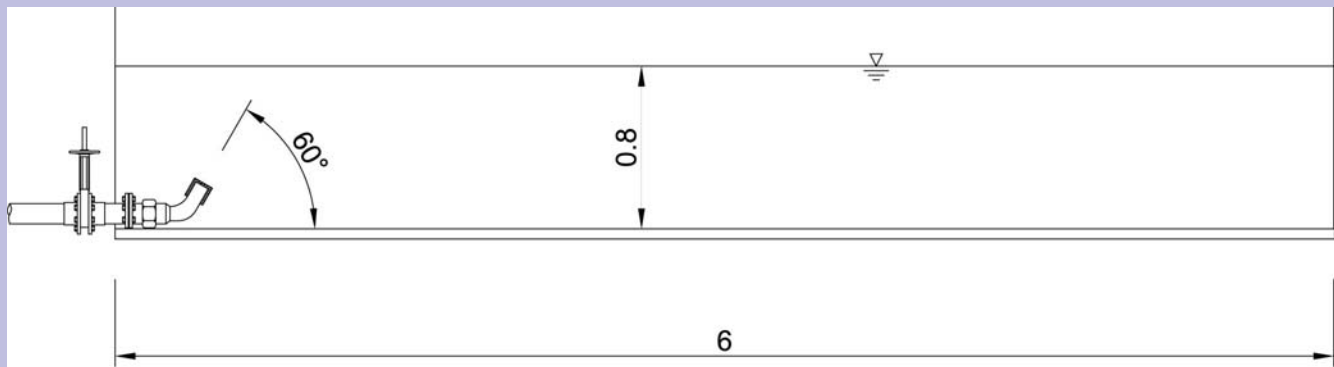
- Similarity:

$$[F_d]_{prototype} = [F_d]_{model} \Rightarrow \left[\frac{z_{max}}{D}\right]_{prototype} = \left[\frac{z_{max}}{D}\right]_{model}$$

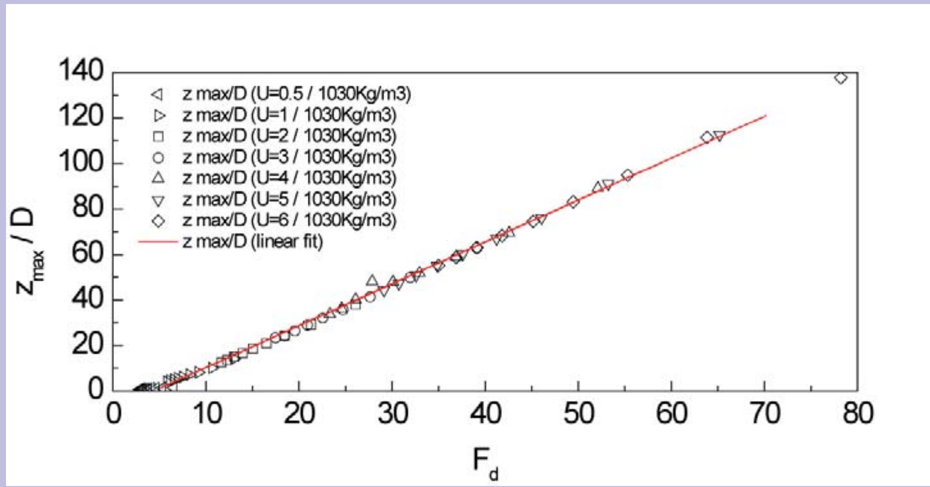
4. Case Study

General Focusing

- Jet integral model applied under global conditions:
  - ✓ $\rho_0/\rho_a \simeq 1.03$
  - ✓ $0.005\, m \leqslant D \leqslant 1.0\, m$.
  - ✓ $0.5\, m/s \leqslant U_0 \leqslant 6\, m/s$.
  - ✓ $\theta \simeq 60^o$.
  - ✓ $H = 0.6\, m$; $h = 0.8\, m$; $z_0 \simeq 0.2\, m$; z_{max} datum at nozzle horizontal plane.

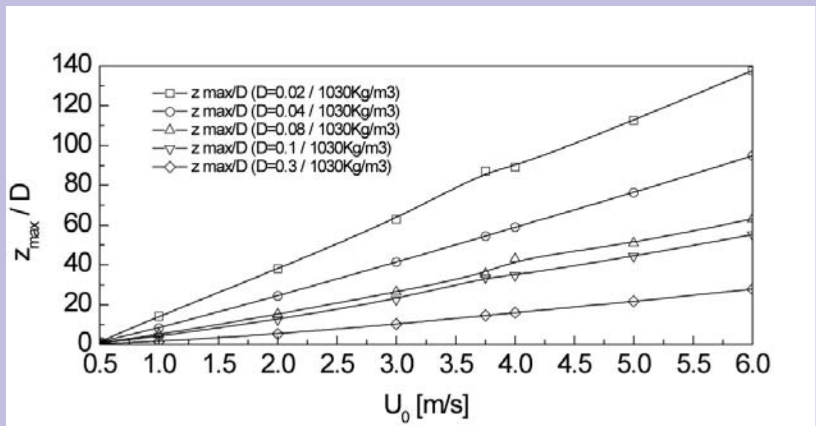


- Jet states represented by z_{max}/D and F_d.



$$\frac{z_{max}}{D} \simeq 1.84 F_d - 8.08$$

- Jet states in terms of U_0: low sensibility regarding changes in U_0 as D increases.



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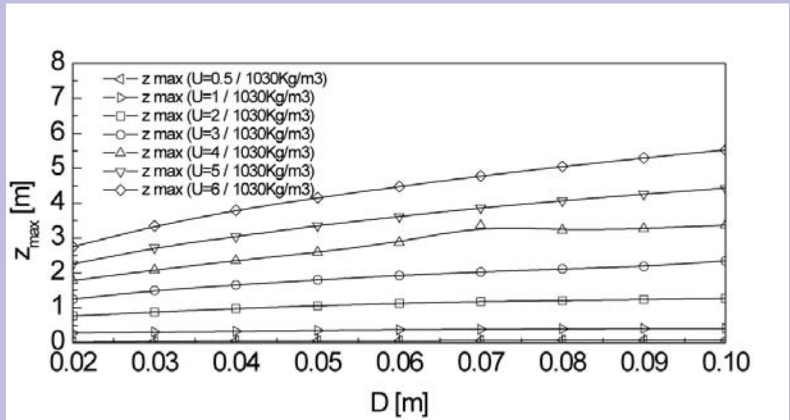
- Kinematics in *near field*: z_{max} not depending on D for $U_0 \lesssim 3.0\, m/s$.



- Interest from experimental point of view: hydrostatic head and tank height as constraints.

- Prototype and model parameters:

$$\left[\frac{\rho_0}{\rho_a}\right]_{prototype} = \left[\frac{\rho_0}{\rho_a}\right]_{model} \simeq 1.03$$

$$\left[\frac{H}{D}\right]_{prototype} \sim \left[\frac{H}{D}\right]_{model} >> 1$$

- Similarity settings:

$$[F_d]_{prototype} = [F_d]_{model}$$

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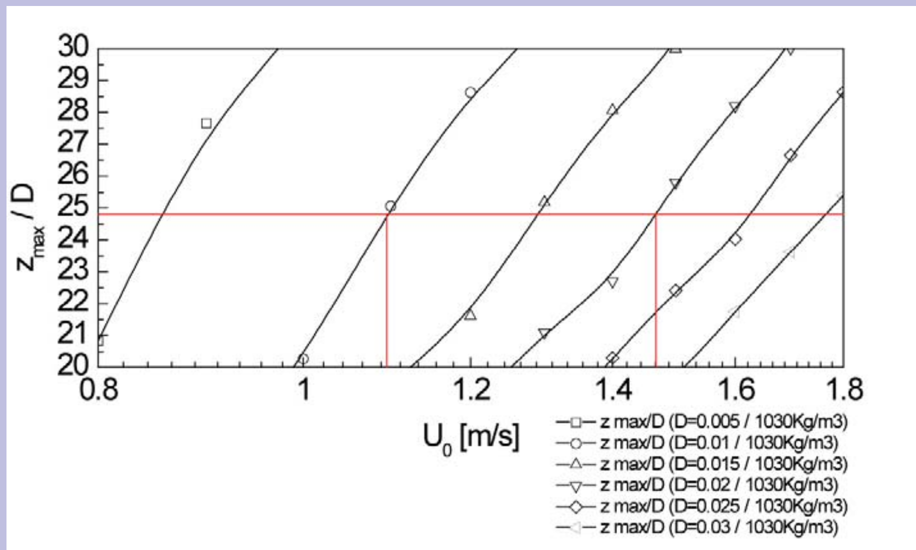
- Jet settings for prototype:

$$F_d = 17.9 \;\Rightarrow\; \frac{z_{max}}{D} \simeq 24.8$$

- Jet states matching $z_{max}/D \simeq 24.8$ condition:

D $[m]$	U_0 $[m/s]$	z_{max} $[m]$	x_{max} $[m]$	$2b_{z\,max}$ $[m]$	Δz $[m]$	Q_0 $[m^3/s]$	Δt $[hh:':'']$
0.005	0.86	0.12	0.25	0.06	+0.7	$0.2 \cdot 10^{-4}$	$\gtrsim 30\,h$
0.01	1.10	0.25	0.50	0.11	+0.5	$0.9 \cdot 10^{-4}$	$8\,h$
0.015	1.29	0.37	0.74	0.16	+0.4	$2.3 \cdot 10^{-4}$	$3\,h$
0.02	1.47	0.50	1.0	0.22	+0.2	$4.6 \cdot 10^{-4}$	$1\,h : 30'$



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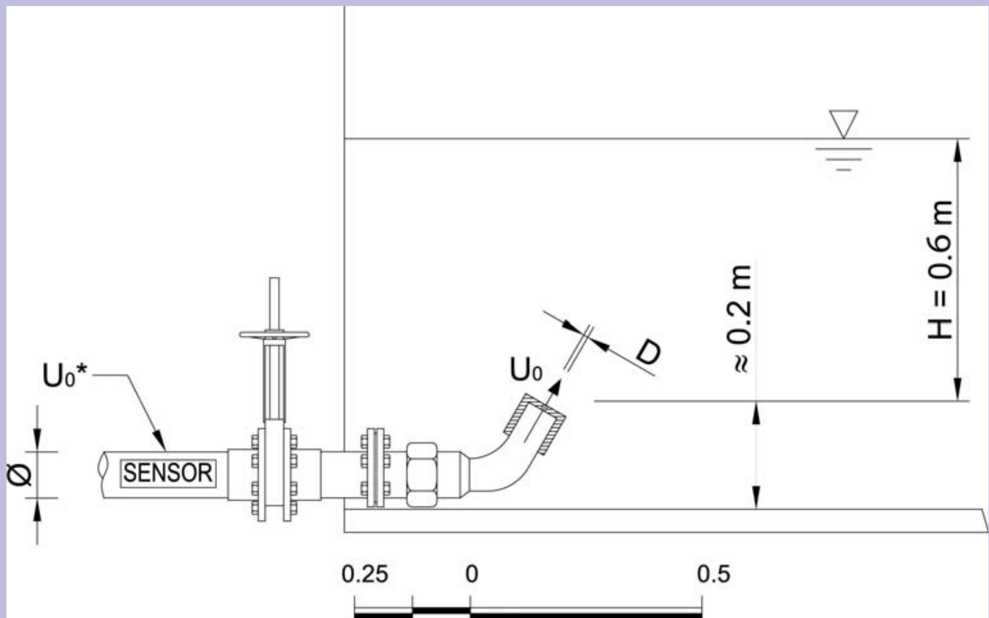
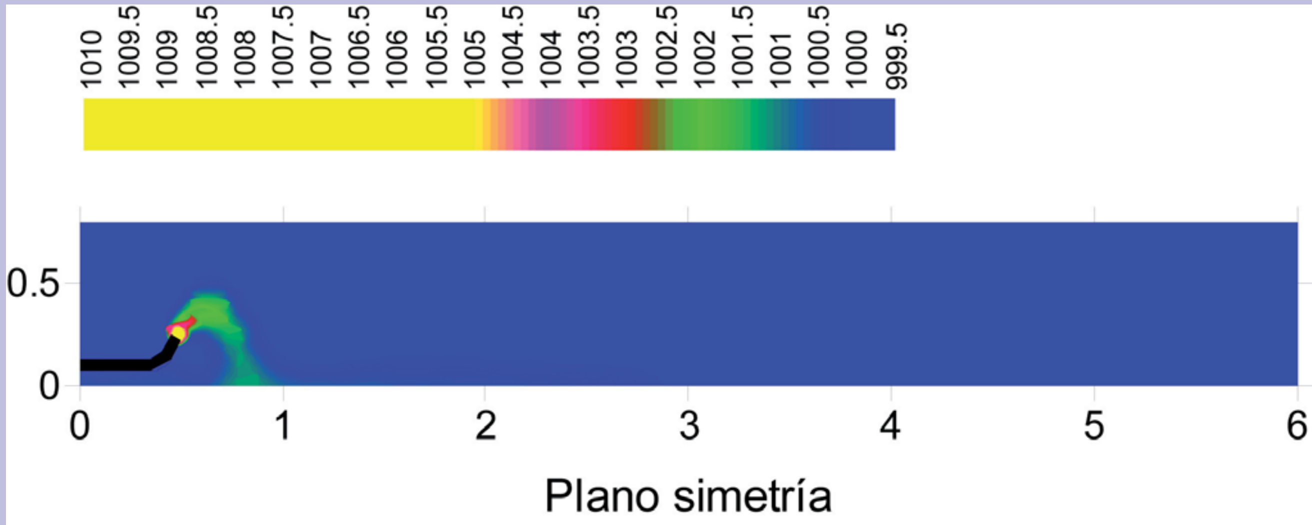
Applied study

- Experimental test parameters matching $z_{max}/D \simeq 24.8$ condition:
  - ✓ $\rho_0/\rho_a \simeq 1.03$.
  - ✓ $D = 0.01\, m$.
  - ✓ $U_0 = 1.1\, m/s$.
  - ✓ $\theta \simeq 60^o$.
  - ✓ $H = 0.6\, m$ above nozzle.



5. Numerical Simulation

- FLUENT® simulation: tank size $6\,m \times 6\,m$, $H = 0.6\,m$, $U_0 = 1.1\,m/s$, $D = 0.01\,m$, $z_2 = 0.1\,m$, $h = 1\,m$, $U_a = 0\,m/s$, $\rho_0/\rho_a = 1.03$, $150\,s$.



- For–the–purpose *software* advantages: full–control over implementation of physical formulation of dilution phenomena.

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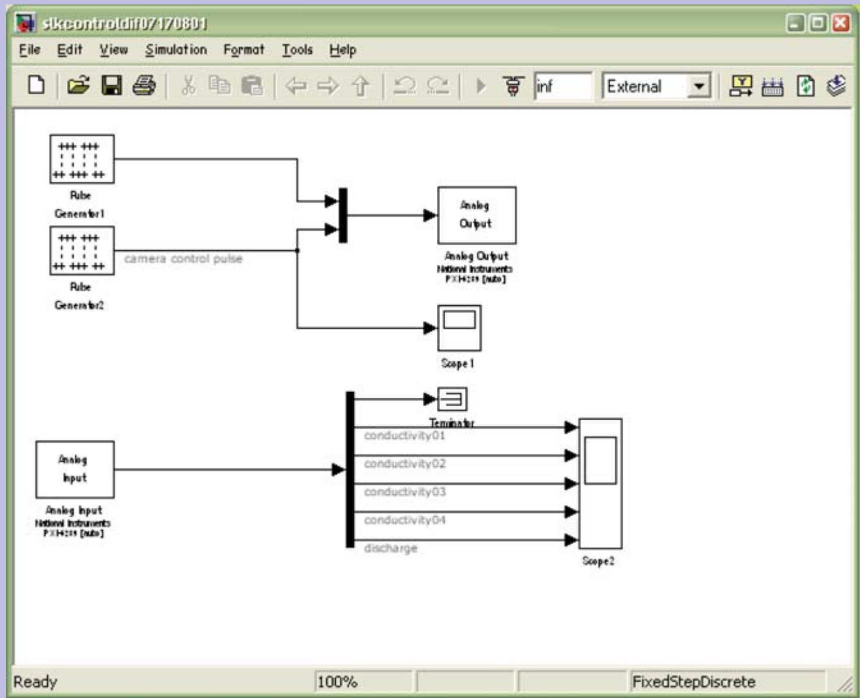
6. Diffusion Tank BEFESA–Grupo de Dinámica de Flujos Ambientales

- Dimensions (width × length × height): $6\,m \times 6\,m \times 2.5\,m$.
- Flow discharge regulated by constant–level storage depot; submersible pump.
- Ultrasonic flow meter; sluice valve.
- Working depth: $\sim 1.5\,m$ max.

- Fluid Dynamics Laboratory Facility, Universidad de Granada.

7. Control and Acquisition

- Simulink®: real–time control of *software–hardware* interface.



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- Time base for control system:

$$T_s = 0.025\,s$$

- Sampling frequency:

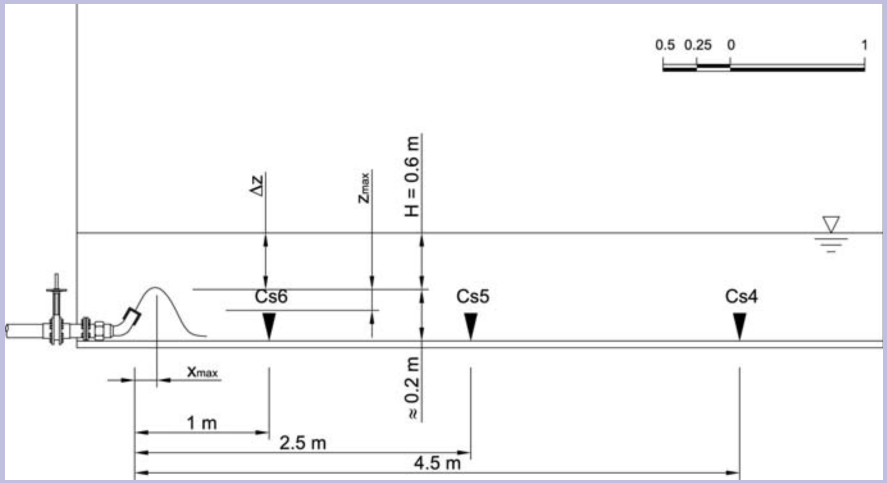
$$f_s = 40\,Hz$$

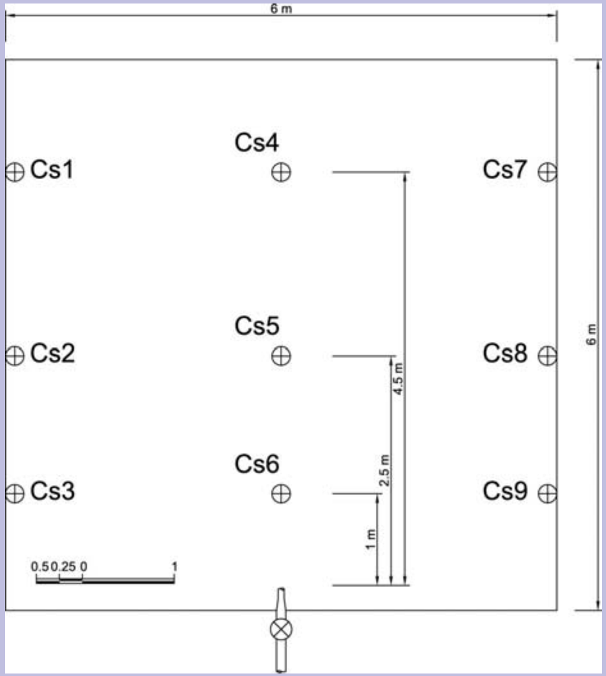
- Pulse generator for image acquisition:

$$T_{pulso} = 5\,samples \;\rightarrow\; 8\,f.p.s.$$

- *software–hardware* interface: pxi–1042q chasis and pxi–6289m cards, 16×2 analog input and 2×2 output channels.
- Conductivity gauges and flow meter:
  - ✓ Response time for conductivity gauges: $5\,s$.
  - ✓ Response time for flow meter: $30\,s - 45\,s$.

- Conductivity gauges location:





8. Results

- Test duration: 1300 s.
- Jet fluid conductivity:

$$C_0 = 83,2\, mS/cm$$

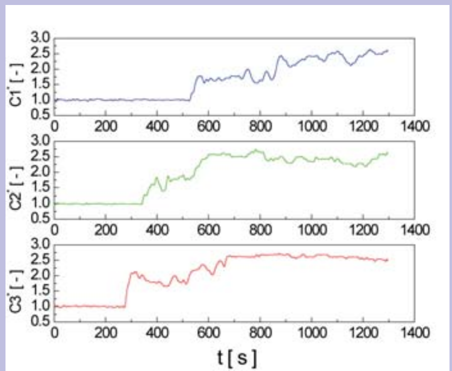
- Initial ambient fluid conductivity:

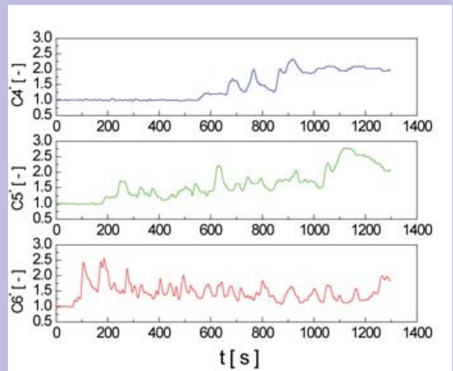
$$C_a = 0.45\, mS/cm$$

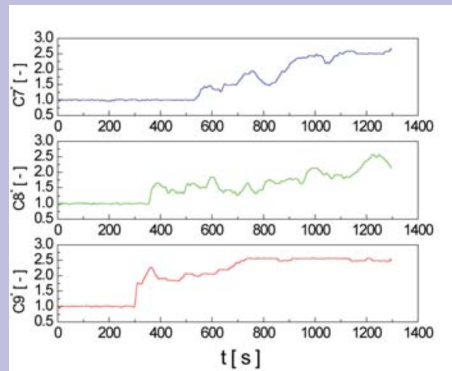
- Normalized conductivity:

$$C^* = C/C_a$$

- Time evolution of normalized conductivity at control points:







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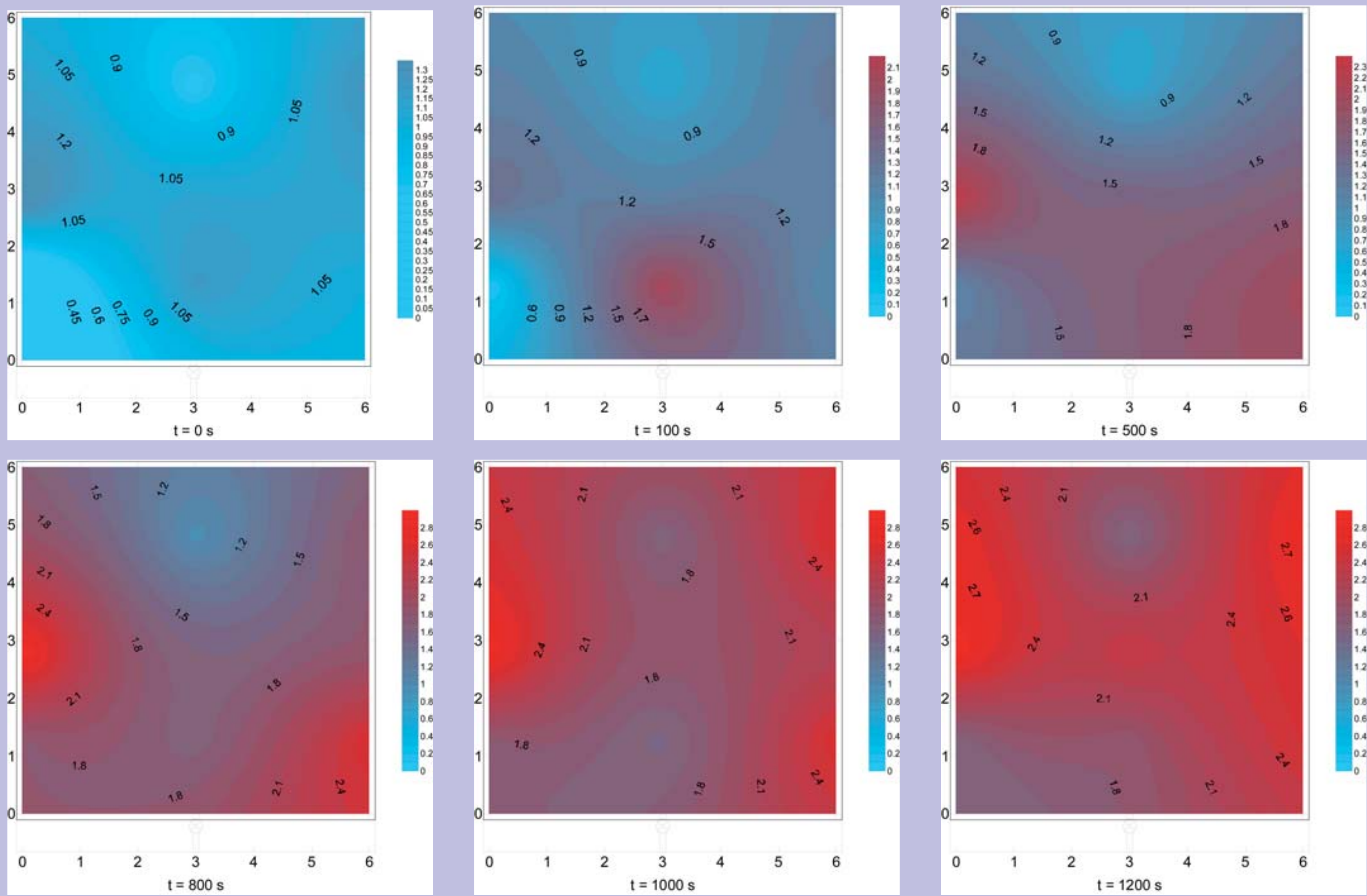
- Spatial evolution of normalized conductivity in $t = 0\ s; 100\ s; 500\ s; 800\ s; 1000\ s; 1200\ s$:



- Conductivity $\rightarrow$ local values less or equal than $2.5C_a$.
- Stationary regime observed at distances $x \gtrsim 350D$ measured from the nozzle.
- Transition *near field–far field* region $\rightarrow$ fluctuations due to concentration–forward motion–dilution cycle.
- Ratio $U_0/U_{axis} \sim O(10^{-2})$ from a general standpoint.
- Negative acceleration $\sim O(10^{-5}\,m/s^2) \rightarrow$ effects of friction and absence of gravity component.

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