SINARA code: Simulation of turbulent mixing on gas interfaces

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SINARA capabilities

- Multi-component single-velocity viscous flows
- Elastic-plastic and strength properties of material
- Turbulence
- Linear heat conduction
- Radiation
- Neutron transport
- Delayed neutrons, resonance self-shielding of cross sections and Doppler effect
- Isotope burn-up

Material models

- Ideal fluid with allowance for several components
- Elasticity, plasticity, compressibility, fracture, melting, evaporation
- Viscous fluid with allowance for several components
- Turbulence
- Geometrical model of radiation

Modules

- Time-dependent hydrodynamics
- Turbulent mixing
- Time-dependent hydrodynamics with elastic-plastic and strength properties
- Heat conduction
- Radiation
- Neutron transport
- Kinetics of neutrons and nuclei

Methods of solving hydrodynamics equations

- ALE method
- An explicit-implicit scheme on staggered meshes
- TVD for the Eulerian phase

Implicit scheme

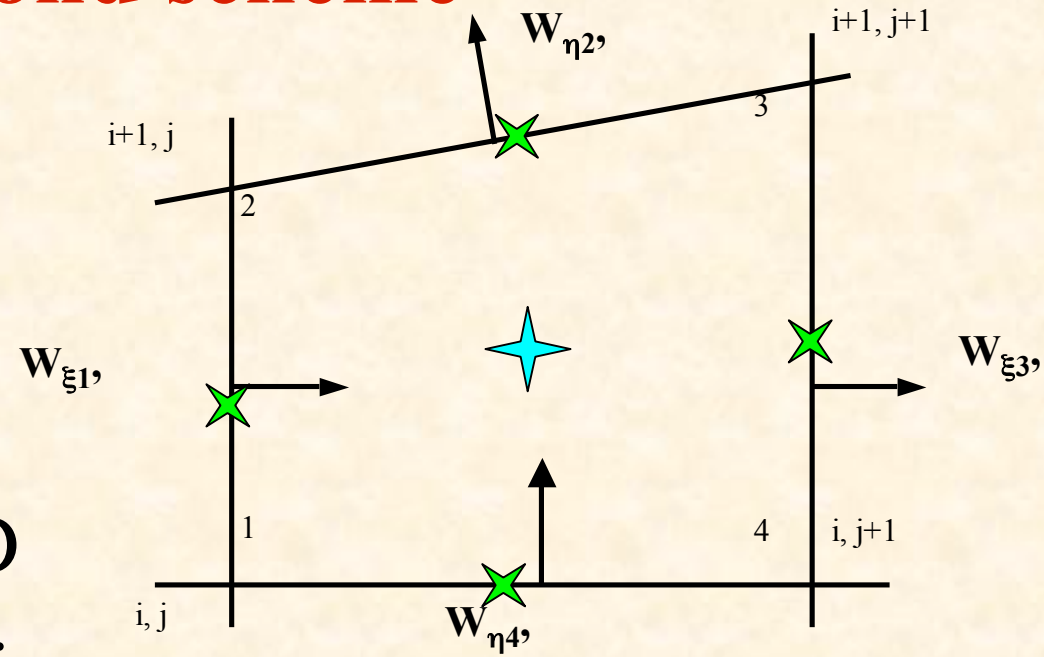
- Equations for viscous pressure

$$\begin{cases} P^{n+1} + \psi \cdot div\, \vec{U}^{n+\frac{1}{2}} = \varphi. \\ \vec{U}^{n+1} + \dfrac{\tau}{\rho^{n+1}} \cdot grad\, P^{n+1} = \vec{U}^{n} \end{cases}$$

- Scheme 1: Velocity interpolation
- Scheme2: Acceleration

$$\vec{W}^{n+\frac{1}{2}} = \frac{1}{\tau}(\vec{U}^{n+1} - \vec{U}^{n})$$

Diamond scheme



- Mesh

$$W_\xi = \vec{W} \cdot \vec{n}_\xi ,$$

$$W_\eta = \vec{W} \cdot \vec{n}_\eta$$

- AD method → 1D
- Additional conditions

$$U_{i+\frac{1}{2}} = \frac{1}{2}\left(U_{i+1} + U_i\right) + \theta_{i+\frac{1}{2}}\left(P_{i+1} - P_i\right),$$

$$P_{i+\frac{1}{2}} = \frac{1}{2}\left(P_{i+1} + P_i\right) + \delta_{i+\frac{1}{2}}\left(U_{i+1} - U_i\right)$$

Diamond without splitting

- Conversion to viscous quantities

$$\vec{u} = \vec{U} + \theta \cdot grad\, P, \quad p = P + \delta \cdot div \vec{U}$$

- Approximation
- Additional relations

$$p_{i+1/2,j+1/2} = \frac{p_{i+1} + p_i}{2} = \frac{p_{j+1} + p_j}{2}$$

$$\left(W_\xi\right)_{j+1/2} = \frac{\left(W_\xi\right)_{i+1} + \left(W_\xi\right)_i}{2}, \quad \left(W_\eta\right)_{j+1/2} = \frac{\left(W_\eta\right)_{j+1} + \left(W_\eta\right)_j}{2}$$

- Iteration of linear algebraic equations

Almost incompressible flow

- M<<1
- Modification of equations – pressure gradient scaling

$$\frac{\partial \rho \vec{u}}{\partial t} + \vec{\nabla}\left(\rho \vec{u}\vec{u}\right) = -\frac{1}{\alpha^2}\vec{\nabla}P$$

- Selection of parameter α

$$\delta P_\alpha / \overline{P} < \varepsilon, \quad \varepsilon << 1, \ \alpha \geq 1$$

Turbulent flow

- Lv model
  - ✓ Navier-Stokes equations
  - ✓ Turbulent viscosity coefficient

$$\mu = \rho L^2 \left(\vec{G} : \vec{\nabla} \vec{u} \right)^{1/2}$$

- Kε model
  - ✓ Solution of hydrodynamics equations and turbulence generation
  - ✓ Turbulent diffusion, turbulent pressure, energy equation
  - ✓ Heat flow and turbulent heat transfer

SINARA testing

- Tests for hydrodynamics and heat conduction equations
  - ✓ A collection of tests - VANT
- Incompressible viscous flow
  - ✓ Air convection in the gravity field
  - ✓ Poiseuille incompressible flow in a cylindrical tube

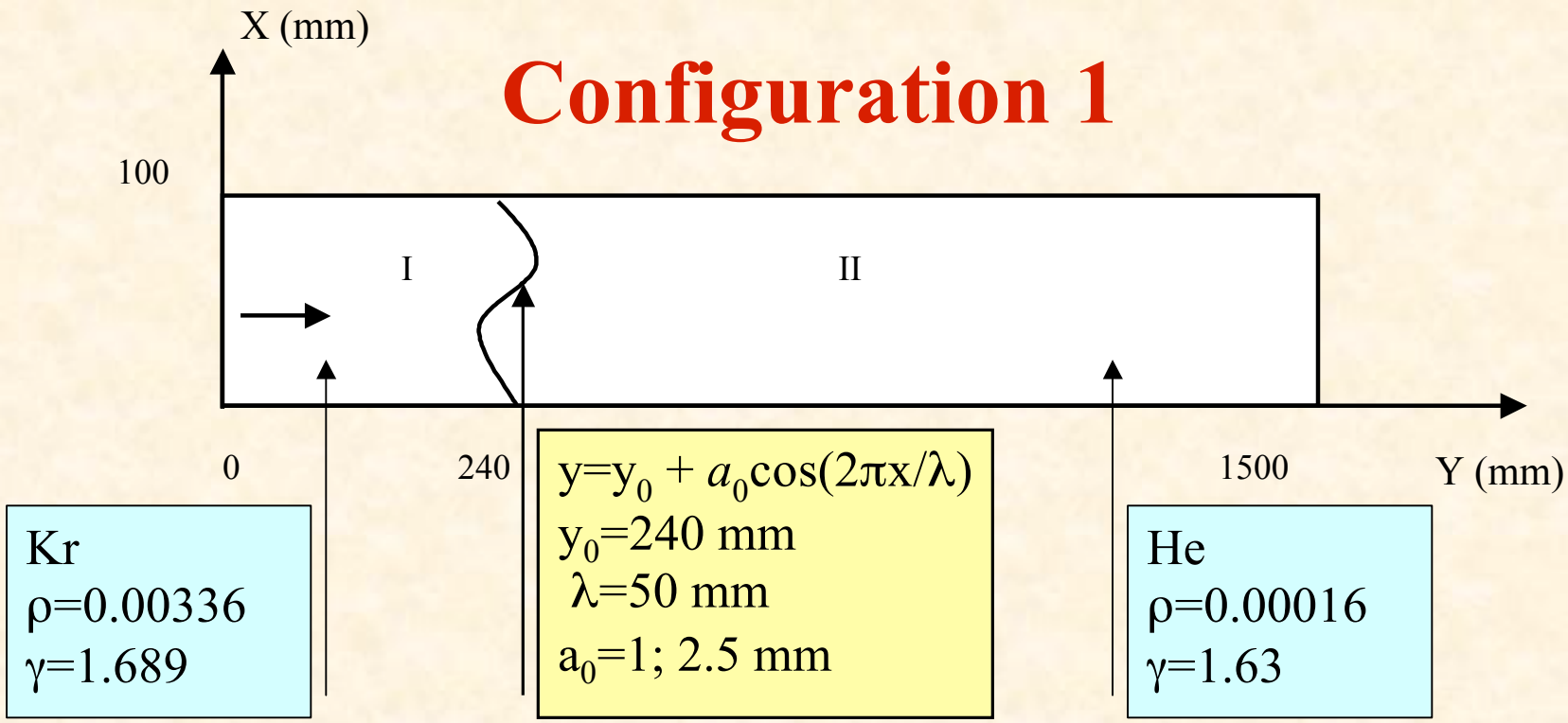
SINARA testing

- Turbulence
  - ✓Flow in a rough tube
  - ✓2D plane steady-state mixing layer
  - ✓Gravity-driven instability
  - ✓Thermal convection
- Advection
  - ✓Shock splitting
  - ✓Triangular prism expansion in vacuum

Straightforward Richtmyer-Meshkov instability simulation

- Electromagnetic shock tube experiments
- Shock traveling from light to heavy fluid
  - ✓Shock: Richtmyer-Meshkov instability
  - ✓Rarefaction: gravitational stability
- Shock traveling from heavy to light fluid
  - ✓Richtmyer-Meshkov and Rayleigh-Taylor instabilities

Configuration 1

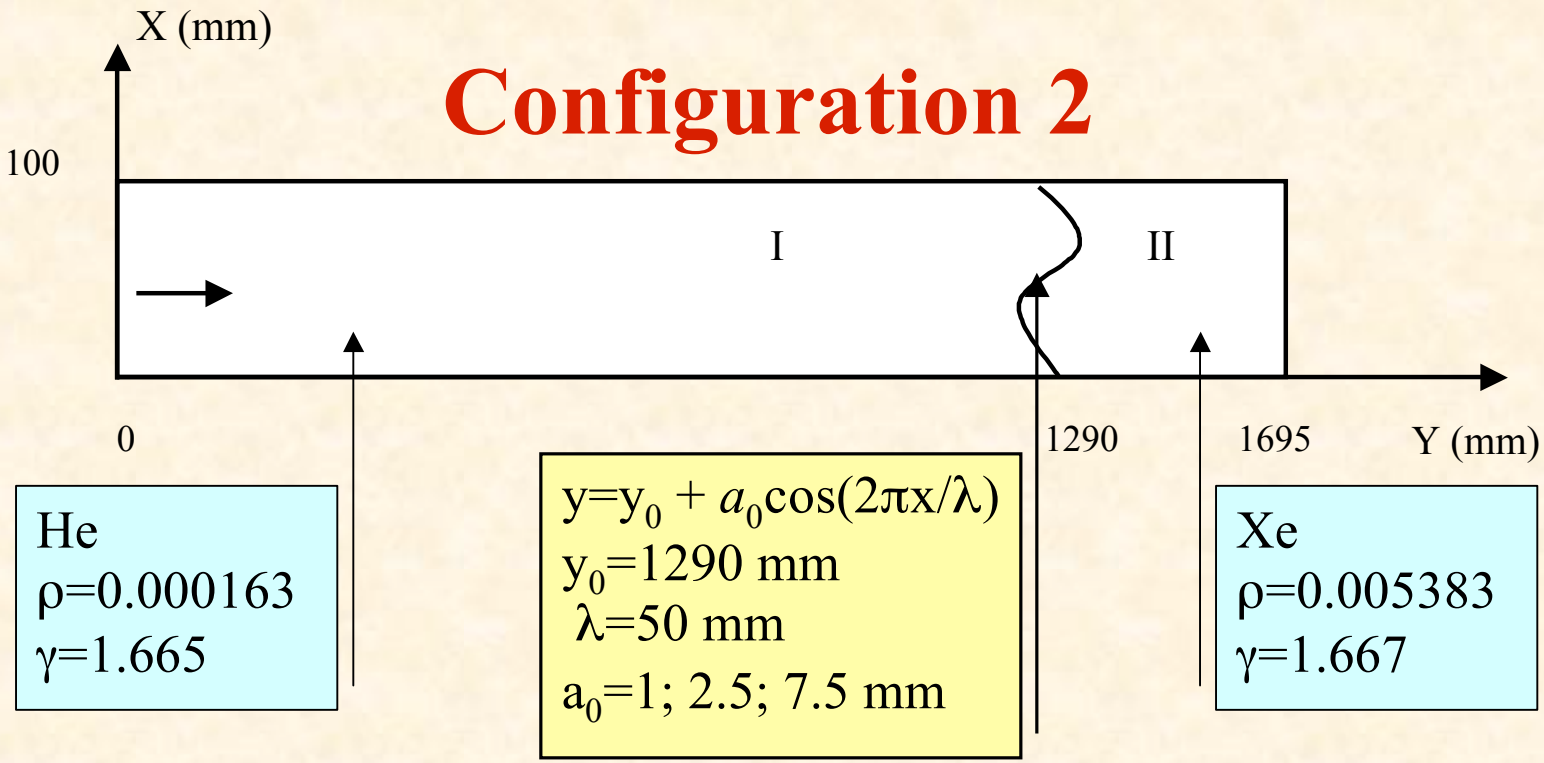


Boundary condition (y=0): $u=U_0\exp(-t/\tau)$,

$U_0=0.948$ mm/μs, $\tau=153.56$ μs

Initial pressure: $p_0=0.984$ bar

Configuration 2



Boundary condition (y=0):

$$P(t) = \begin{cases} P_n, & 0 \le t \le t^* \\ P^* \exp(-2t/\tau)\sin^2(2\pi t/T), & t^* \le t \le T/2 \\ 0, & t \ge T/2 \end{cases}$$

P_n=1.217 bar, t^*=1.2 μs, P^*=123.3 bar, T=75 μs, τ=97.4 μs

Initial pressure: p_0=0.976 bar

Mixture models

- Homogeneous $\left(\bar{T}, \bar{\rho}, m_1, \ldots, m_k, n_1, \ldots, n_k\right)$
- Heterogeneous

$$\left(T_1, \ldots, T_k, \rho_1, \ldots, \rho_k, m_1, \ldots, m_k, V_1, \ldots, V_k, n_1, \ldots, n_k\right)$$

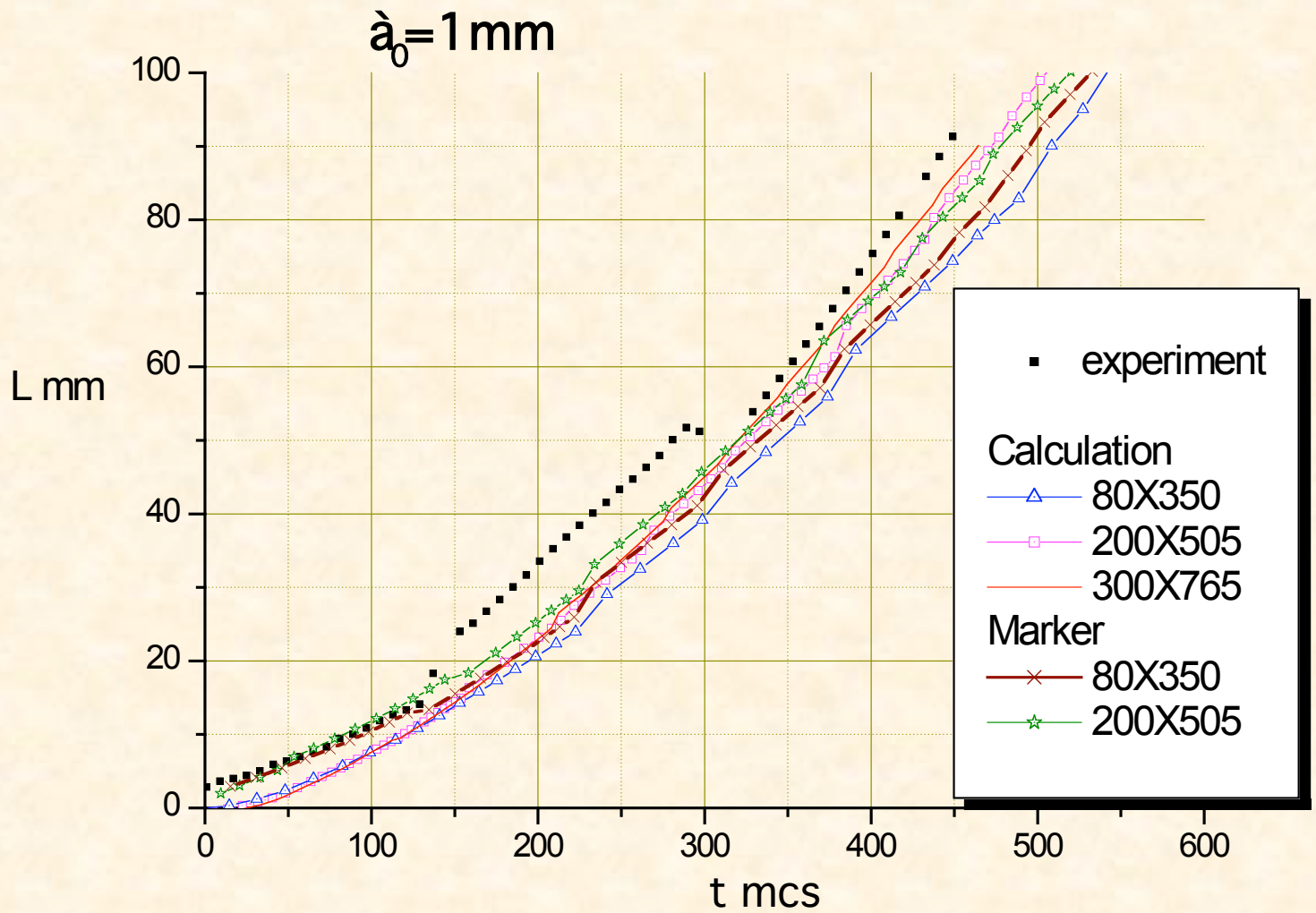
$$\bar{P} = \sum_{i=1}^{k} \alpha_i \cdot \xi_i \cdot P_i\left(\rho_i, T_i\right), \ \bar{\varepsilon} = \sum_{i=1}^{k} c_i \cdot \bar{\varepsilon}_i\left(\rho_i, T_i\right)$$

✓Equal compressibility of mixed materials

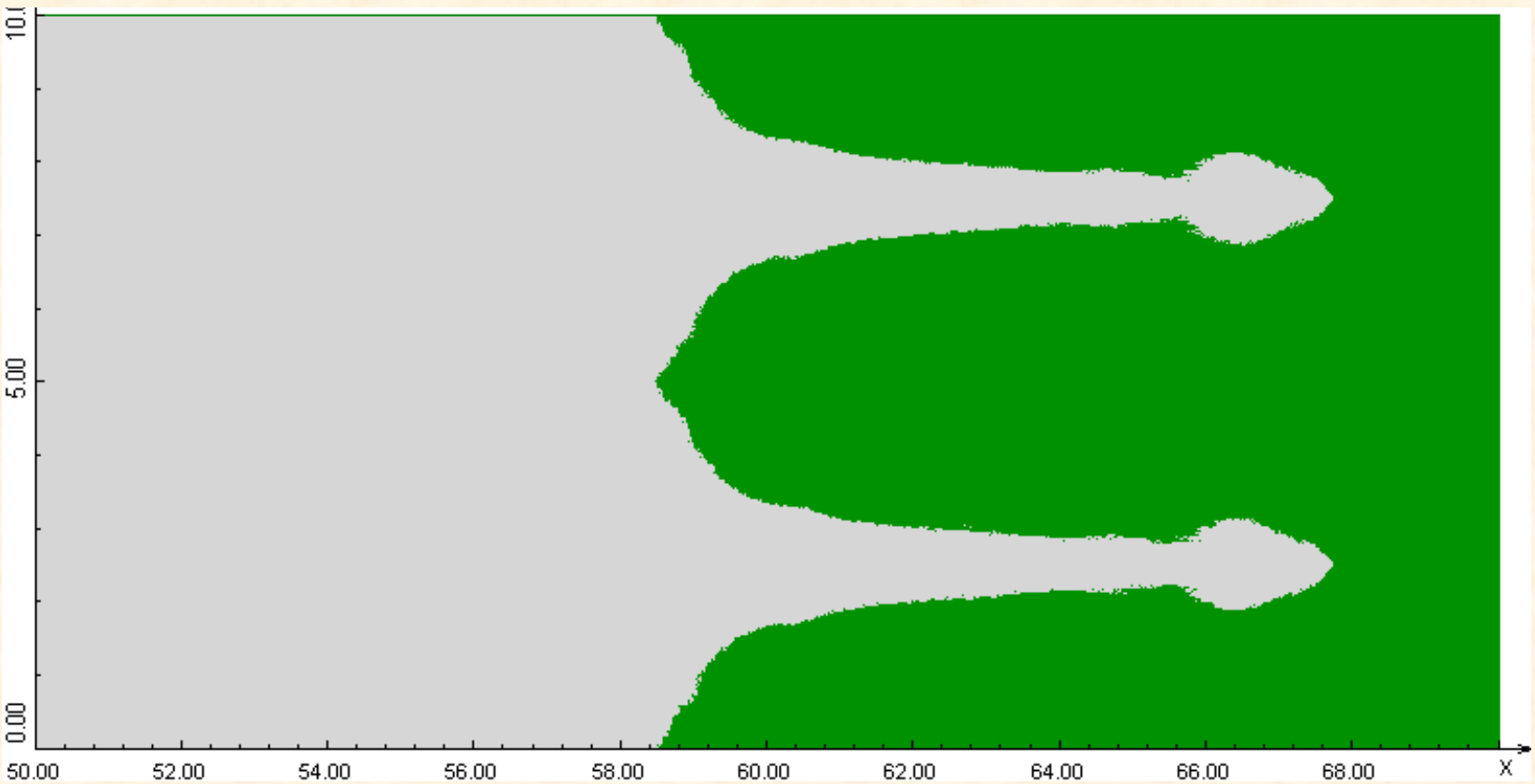
✓Dynamic equilibrium

✓Equal pressure increments

Results: Configuration 1

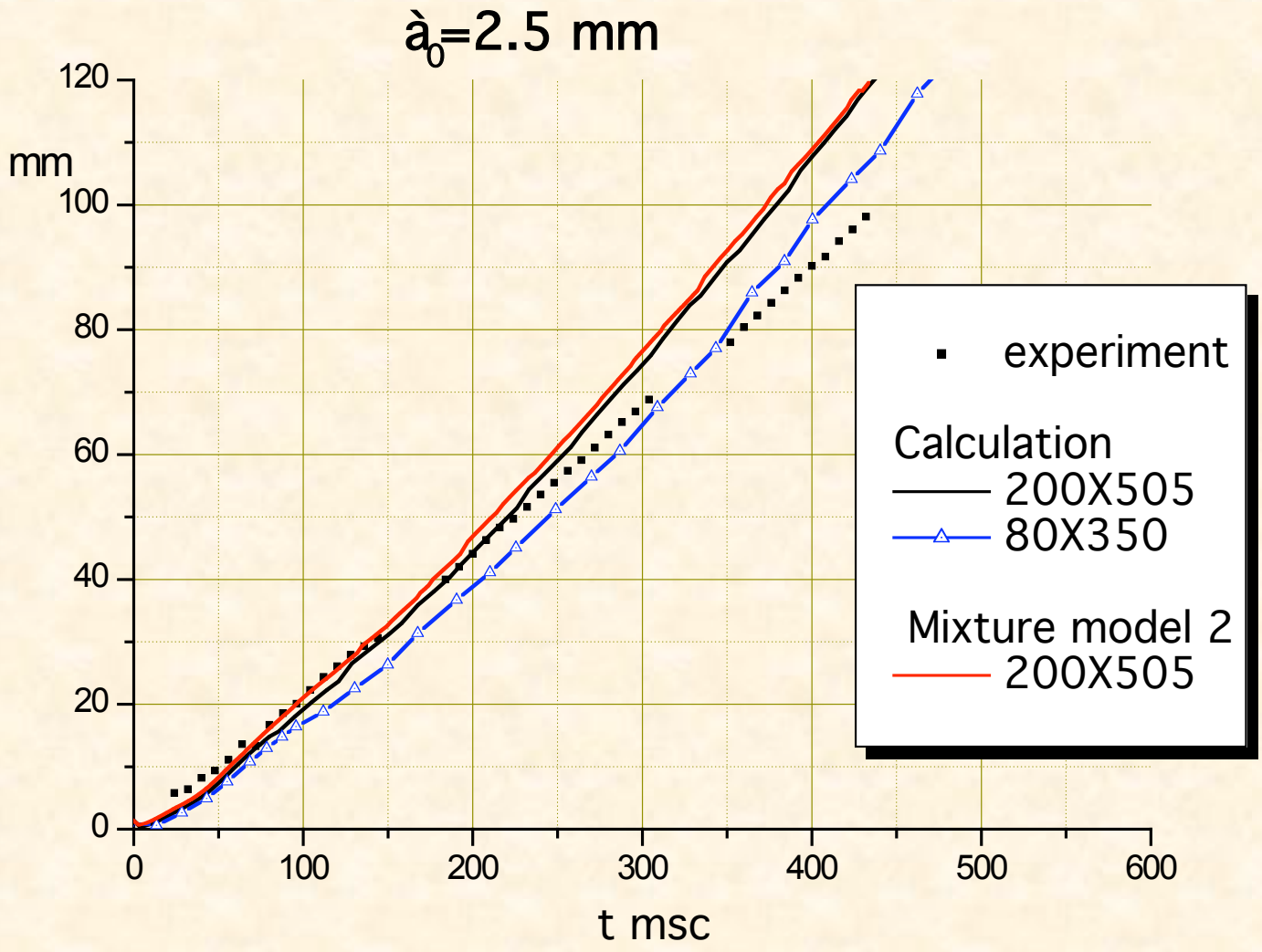


Results: Configuration 1

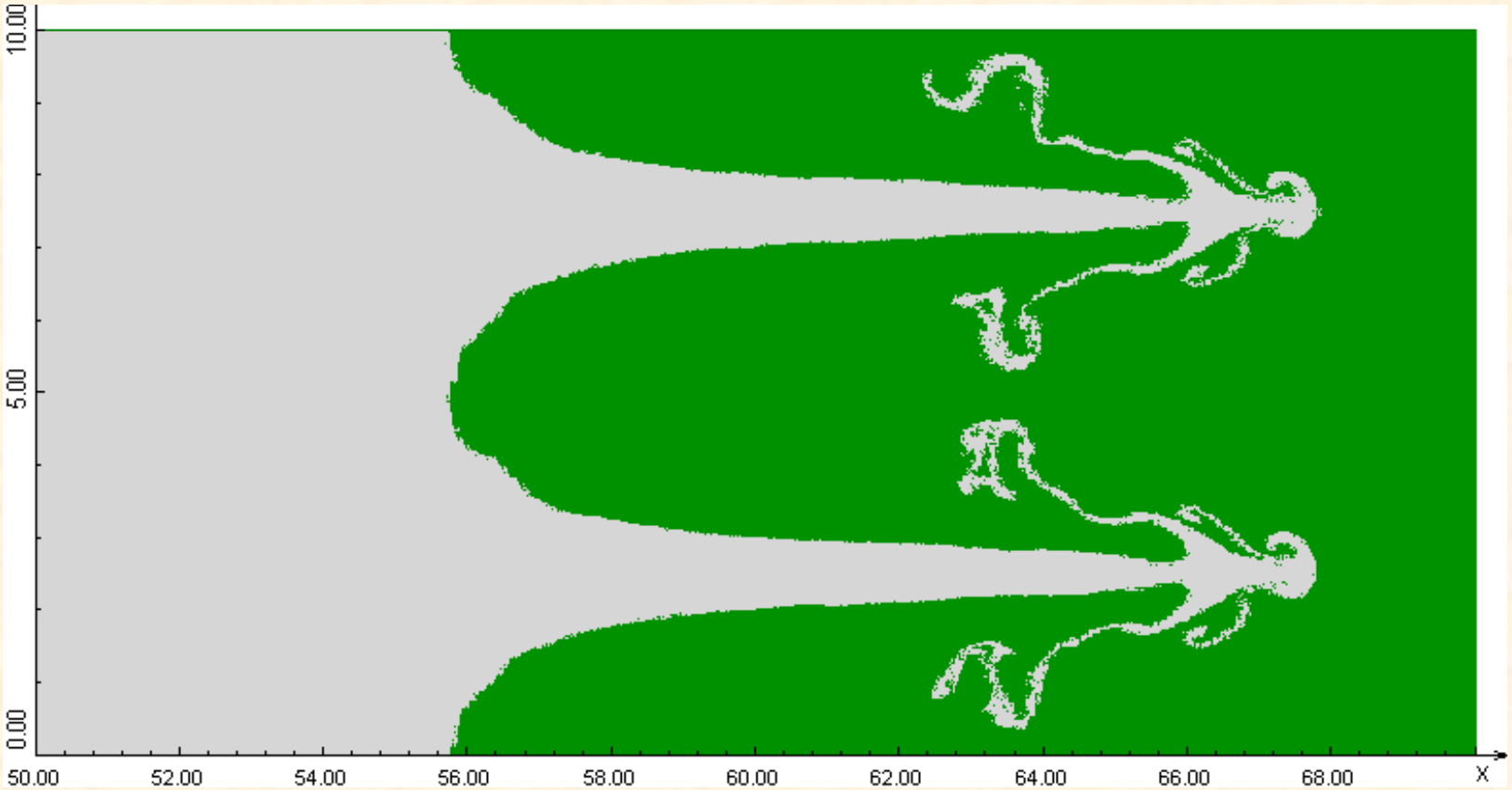


a_0=1 mm

Results: Configuration 1

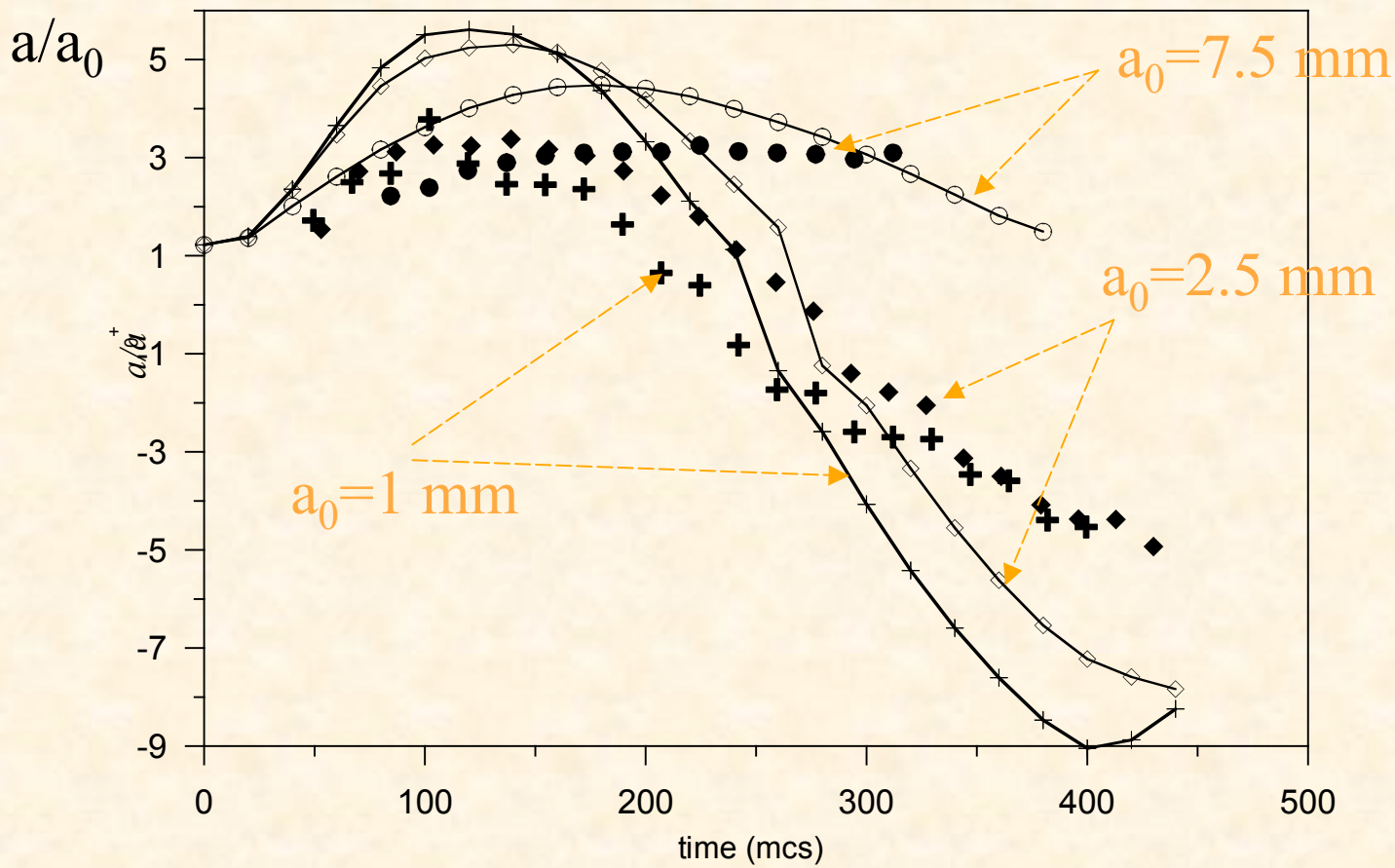


Results: Configuration 1



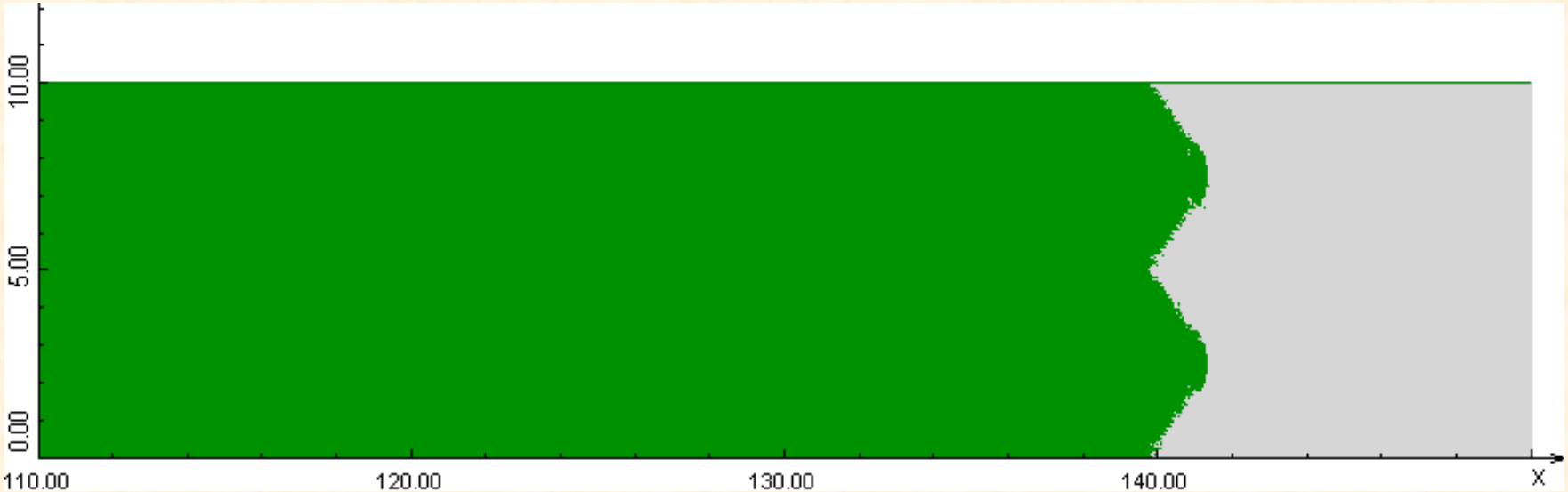
a_0=2.5 mm

Results: Configuration 2



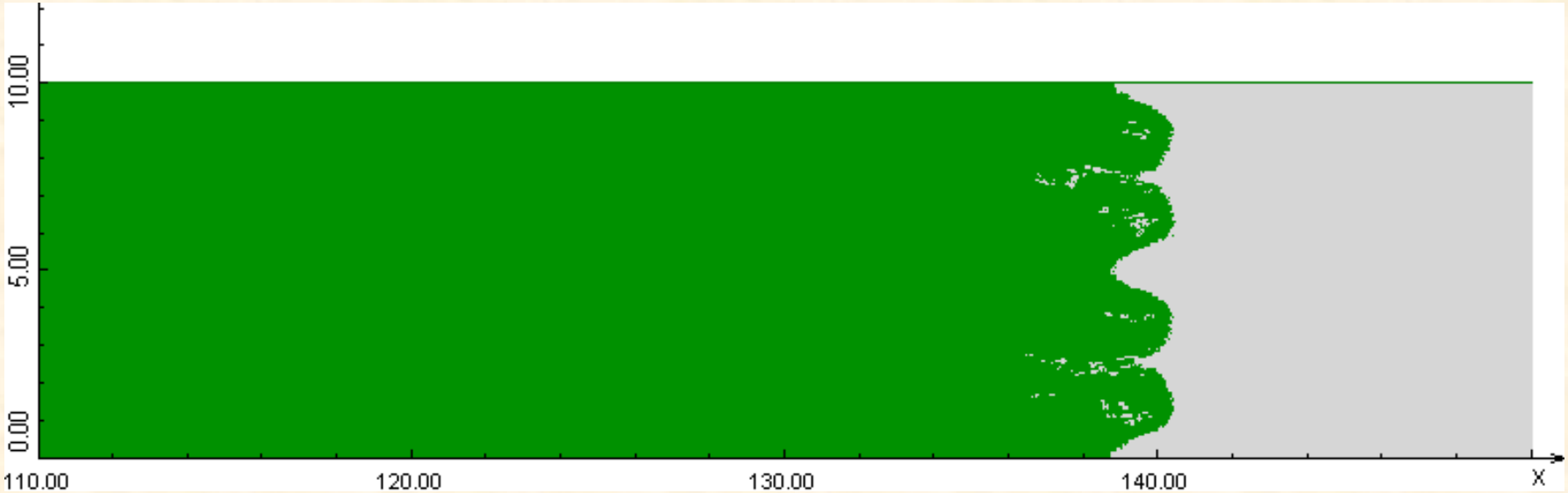
Results: Configuration 2

a_0=1 mm



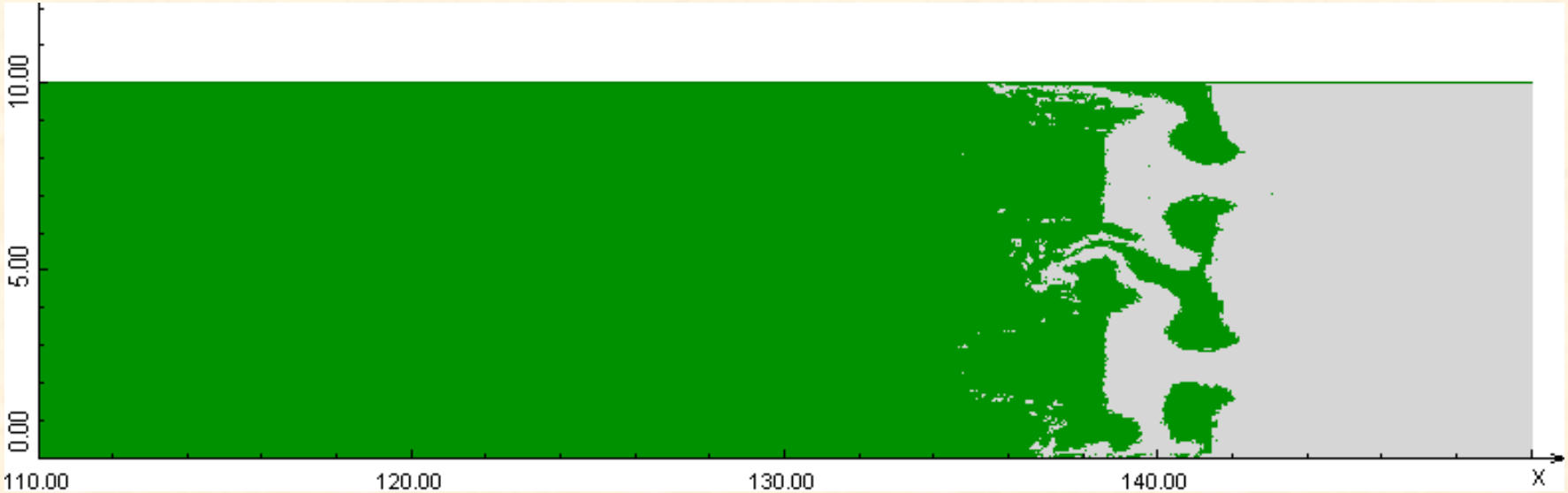
Results: Configuration 2

a_0=2.5 mm



Results: Configuration 2

a_0=7.5 mm



Discussion: Configuration 1

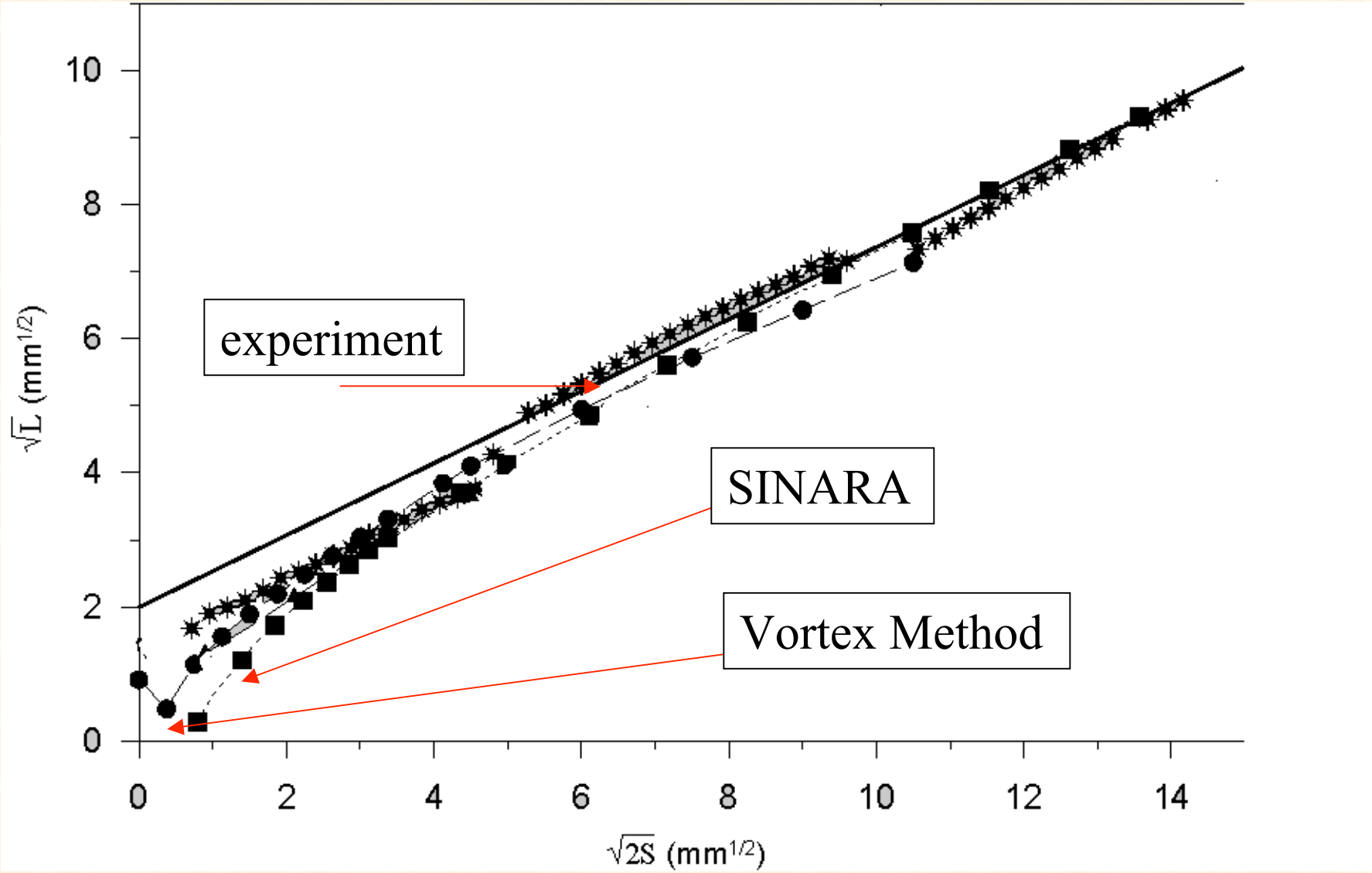
- Real mixing width

$$\sqrt{\hat{L}} = \sqrt{L_0} + \sqrt{L}$$

- Self-similar mixing width $L = \alpha A 2S$
  - ✓ A = Atwood's number $A = (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$
  - ✓ S = deceleration length $S = \Delta U\, t - \Delta\hat{x}$
- Value for α

$$\sqrt{\alpha A} = d\sqrt{\hat{L}} / d(\sqrt{2S}) \qquad \alpha_{\text{exper}} \approx 0.26$$

Variation of α for configration 1



Thank you