

# Saiph CFD applications

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## i 1D Linear Advection - Sine Wave

### Problem Specification

**Use Case.** Linear Advection

Spatial domain:  $0 \leq x < 1$  meters, periodic boundary conditions

Governing equations: 1D Linear Advection Equation

$$\frac{\partial \phi}{\partial t} = -\mathbf{u} \cdot \nabla \phi$$

Initial conditions:

$$\phi(x) = \sin(2\pi x)$$

$$\mathbf{u} = 1 \text{ m/s}$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

### Simulation details

$$\Delta x = 1 \text{ mm}$$

$$\Delta t = 1 \text{ ms}$$

$$nsteps = 1000$$

Forward in-time integration using Euler method:  $\mathcal{O}(t)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

### Results

Output results at three time-steps,  $t = 0s$ ,  $t = 0.5s$  and  $t = 1s$  are presented in Figure 1. The  $L_2$  norm has been computed over the  $\phi$  variable taking the initial conditions as the analytic solution. The output simulation presents no truncation error  $\mathbf{L}_2 = \mathbf{0}$

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

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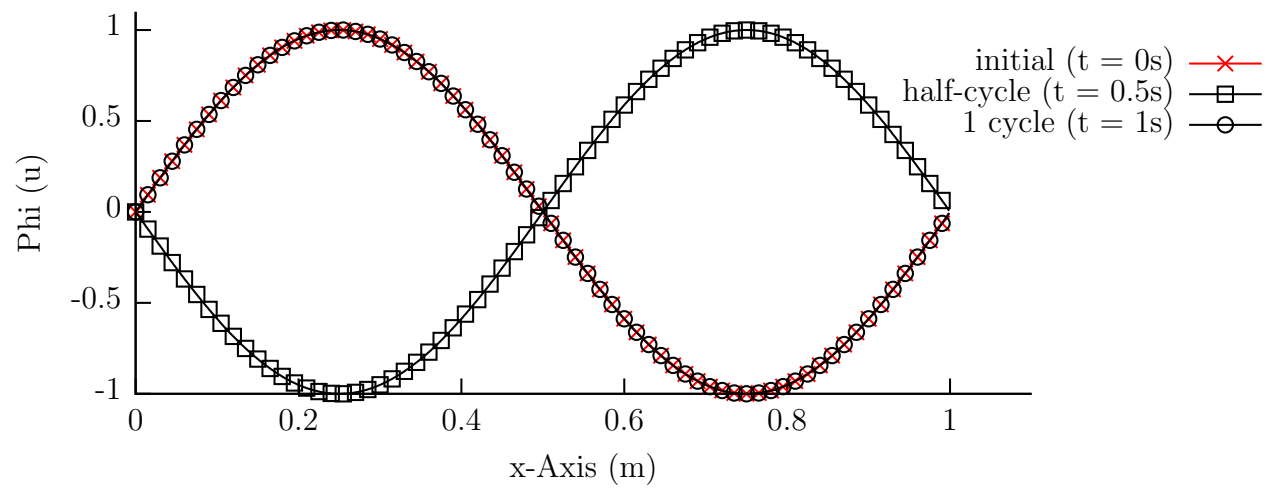


Figure 1: Phi profile at different time-steps.

## ii 1D Linear Advection - Discontinuous Waves

### Problem Specification

**Use Case.** Linear Advection

Spatial domain:  $-1 \leq x < 1$  meters, periodic boundary conditions

Governing equations: 1D Linear Advection Equation

$$\frac{\partial \phi}{\partial t} = -\mathbf{u} \cdot \nabla \phi$$

Initial conditions:

$$\phi(x) = \begin{cases} \exp\left(-\log(2)\frac{(x+7)^2}{0.0009}\right) & -0.8 \leq x \leq -0.6 \\ 1 & -0.4 \leq x \leq -0.2 \\ 1 - |10(x - 0.1)| & 0 \leq x \leq 0.2 \\ \sqrt{1 - 100(x - 0.5)^2} & 0.4 \leq x \leq 0.6 \\ 0 & \text{otherwise} \end{cases}$$

$$\mathbf{u} = 1 \text{ m/s}$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

### Simulation details

$$\Delta x = 1 \text{ mm}$$

$$\Delta t = 1 \text{ ms}$$

$$nsteps = 2000$$

Forward in-time integration using Euler method:  $\mathcal{O}(t)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

### Results

Output results at two time-steps,  $t = 0s$  and  $t = 2s$  are presented in Figure 2.

The  $L_2$  norm has been computed over the  $\phi$  variable taking the initial conditions as the analytic solution. The output simulation presents no truncation error  $\mathbf{L}_2 = 0$

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

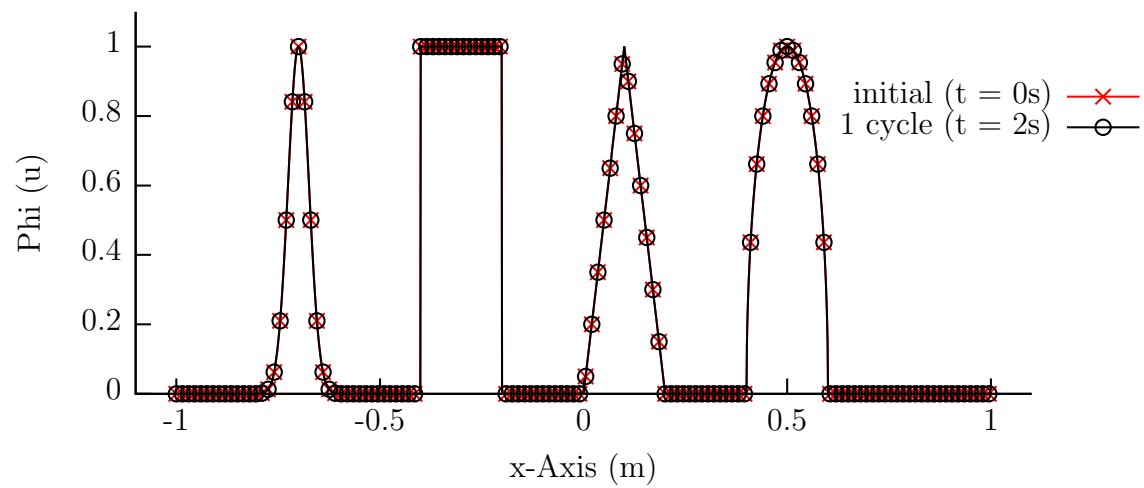


Figure 2:  $\Phi$  profile at different time-steps.

### iii 1D Linear Diffusion - Sine Wave

#### Problem Specification

**Use Case.** Linear Diffusion

Spatial domain:  $0 \leq x < 1$  meters, periodic boundary conditions

Governing equations: 1D Linear Diffusion Equation

$$\frac{\partial \phi}{\partial t} = \nabla \cdot (\nu \nabla \phi)$$

Initial conditions:

$$\phi(x) = \sin(2\pi x)$$

$$\nu = 0.001 \text{ m}^2/\text{s}$$

The Saiph's code specification can be checked at:

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#### Simulation details

$$\Delta x = 12.5 \text{ mm}$$

$$\Delta t = 50 \text{ ms}$$

$$nsteps = 200$$

Forward in-time integration using 3<sup>rd</sup> order Runge-Kutta method:  $\mathcal{O}(t^3)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

#### Results

Output results at three time-steps,  $t = 0s$ ,  $t = 5s$  and  $t = 10s$  are presented in Figure 3.

The  $L_2$  norm has been computed over the  $\phi$  variable taking the analytic solution as reference:

$$\phi(x, t) = e^{-\nu 4\pi^2 t} \sin(2\pi x)$$

The final output simulation ( $t = 10s$ ), presents an error of  $\mathbf{L_2 = 1.4 \cdot 10^{-7}}$

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

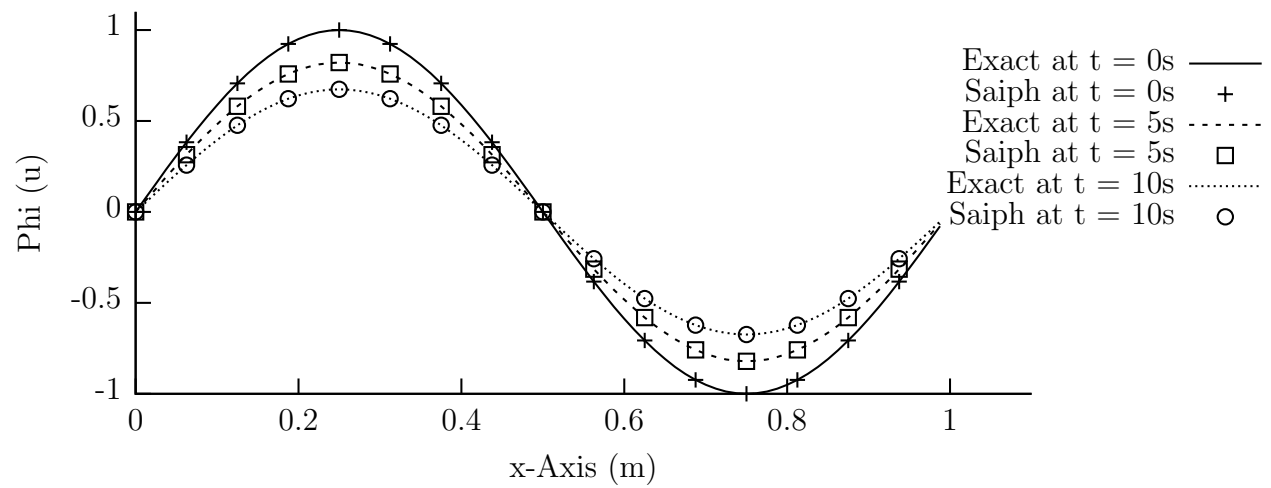


Figure 3: Phi profile at different time-steps.

## iv 1D Euler Equations - Sod Shock Tube

This problem corresponds to the well known shock tube originally proposed by Sod [6]. It is a transient case consisting of a one-dimensional tube, closed at its ends and divided into two equal regions by a thin diaphragm. Each region is filled with the same gas, but with different thermodynamic parameters. The fluid is initially at rest and starts to move because of the sudden breakdown of the diaphragm, the discontinuous initial condition of the left and right states entails a shock wave that propagates to both left and right sides. Figure 4 schematizes the configuration of this test [2].

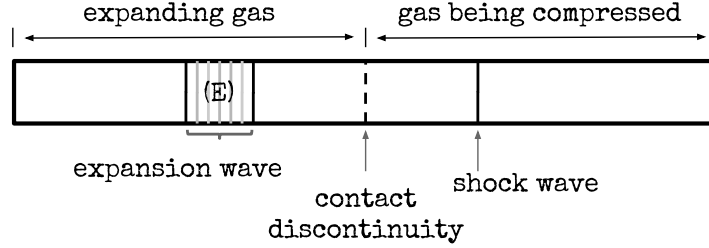


Figure 4: Schema of waves propagating in the tube after the diaphragm breakdown ( $t > 0$ ).

### Problem Specification

**Use Case.** Sod shock tube

Spatial domain:  $0 \leq x < 1$  meters

Governing equations: 1D Euler equations, continuity, momentum, energy and state.

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u})$$

$$\frac{\partial(\rho u_i)}{\partial t} = - \left[ \rho \mathbf{u} \cdot \nabla u_i + u_i \nabla \cdot (\rho \mathbf{u}) + \frac{\partial p}{\partial x_i} \right]$$

$$\frac{\partial(\rho E)}{\partial t} = - [\mathbf{u} \cdot \nabla \rho E + \rho E \nabla \cdot \mathbf{u} + \mathbf{u} \cdot \nabla p + p \nabla \cdot \mathbf{u}]$$

$$p = (\gamma - 1) \left( (\rho E) - \frac{1}{2} (\rho \mathbf{u}) \mathbf{u} \right)$$

Initial conditions:

$$\gamma = 1.4$$

$$\mathbf{u} = 0 \text{ m/s}$$

$$\rho(x) = \begin{cases} 1 \text{ kg/m}^3 & 0 \leq x < 0.5 \\ 0.125 \text{ kg/m}^3 & 0.5 \leq x \leq 1 \end{cases}$$



$$\rho E(x) = \begin{cases} 2.5 \text{ kg/ms}^2 & 0 \leq x < 0.5 \\ 0.25 \text{ kg/ms}^2 & 0.5 \leq x \leq 1 \end{cases}$$

$$p(x) = \begin{cases} 1 \text{ Pa} & 0 \leq x < 0.5 \\ 0.1 \text{ Pa} & 0.5 \leq x \leq 1 \end{cases}$$

Boundary conditions:

Symmetric boundary condition (Neumann BCs)

$$\frac{\partial \rho}{\partial x} = 0 \text{ kg/m}^4 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial(\rho E)}{\partial x} = 0 \text{ kg/m}^2 \text{s}^2 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial(\rho \mathbf{u})}{\partial x} = 0 \text{ kg/m}^3 \text{s} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial p}{\partial x} = 0 \text{ Pa/m} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

## Simulation details

$\Delta x = 2.5 \text{ mm}$

$\Delta t = 0.2 \text{ ms}$

$nsteps = 1000$

Forward in-time integration using 3<sup>rd</sup> order Runge-Kutta method:  $\mathcal{O}(t^3)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

## Results

Output results at final time,  $t = 0.2s$  are presented in Figure 5, against analytic solutions.

The  $L_2$  norm has been computed over the density, pressure and velocity variables taking the analytic solution as reference. The final output simulation, presents an error of

$$\mathbf{L}_{2-\rho} = 1.2 \cdot 10^{-2}, \mathbf{L}_{2-p} = 1.1 \cdot 10^{-2}, \mathbf{L}_{2-u} = 3.7 \cdot 10^{-2}$$

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

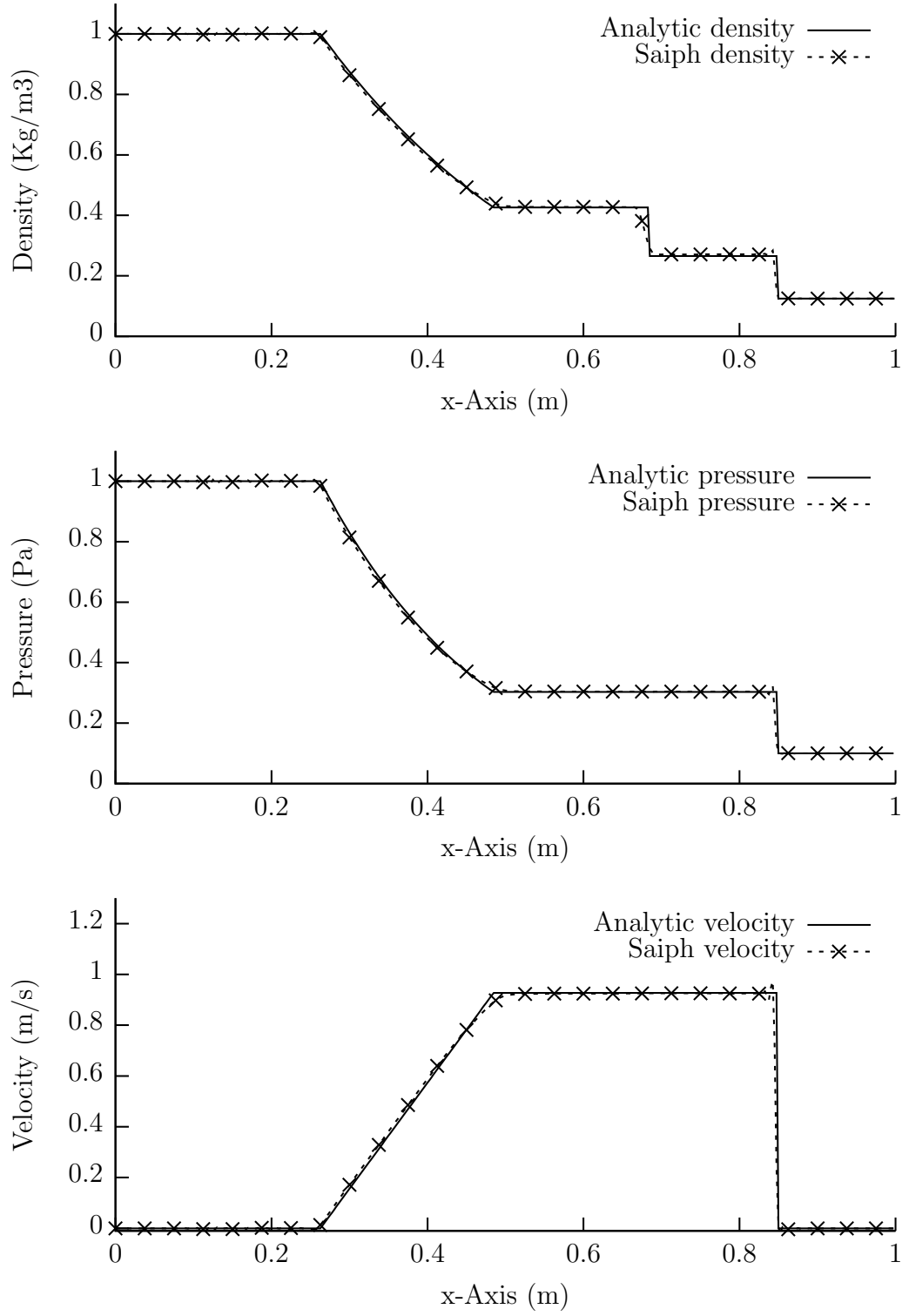


Figure 5: Variable profiles at  $t = 0.2s$  for the Sod Tube problem.

## v 1D Euler Equations - Lax Shock Tube

Similar to Sod shock tube use-case with different initial conditions.

### Problem Specification

**Use Case.** Lax shock tube

Spatial domain:  $0 \leq x < 1$  meters

Governing equations: 1D Euler equations, continuity, momentum, energy and state.

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u})$$

$$\frac{\partial(\rho u_i)}{\partial t} = - \left[ \rho \mathbf{u} \cdot \nabla u_i + u_i \nabla \cdot (\rho \mathbf{u}) + \frac{\partial p}{\partial x_i} \right]$$

$$\frac{\partial(\rho E)}{\partial t} = - [\mathbf{u} \cdot \nabla \rho E + \rho E \nabla \cdot \mathbf{u} + \mathbf{u} \cdot \nabla p + p \nabla \cdot \mathbf{u}]$$

$$p = (\gamma - 1) \left( (\rho E) - \frac{1}{2} (\rho \mathbf{u}) \cdot \mathbf{u} \right)$$

Initial conditions:

$$\gamma = 1.4$$

$$\rho(x) = \begin{cases} 0.445 \text{ kg/m}^3 & 0 \leq x < 0.5 \\ 0.5 \text{ kg/m}^3 & 0.5 \leq x \leq 1 \end{cases}$$

$$\rho \mathbf{u}(x) = \begin{cases} 0.311 \text{ kg/m}^2 \text{s} & 0 \leq x < 0.5 \\ 0 \text{ kg/m}^2 \text{s} & 0.5 \leq x \leq 1 \end{cases}$$

$$\rho E(x) = \begin{cases} 8.928 \text{ kg/m} \text{s}^2 & 0 \leq x < 0.5 \\ 1.4275 \text{ kg/m} \text{s}^2 & 0.5 \leq x \leq 1 \end{cases}$$

Boundary conditions:

Symmetric boundary condition (Neumann BCs)

$$\frac{\partial \rho}{\partial x} = 0 \text{ kg/m}^4 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial(\rho E)}{\partial x} = 0 \text{ kg/m}^3 \text{s}^2 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial(\rho \mathbf{u})}{\partial x} = 0 \text{ kg/m}^3 \text{s} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial p}{\partial x} = 0 \text{ Pa/m} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

The Saiph's code specification can be checked at:

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## Simulation details

$\Delta x = 5$  mm

$\Delta t = 1$  ms

$nsteps = 80$

Forward in time integration using 3<sup>rd</sup> order Runge-Kutta method:  $\mathcal{O}(t^3)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

## Results

Output results at final time,  $t = 0.08s$  are presented in Figure 6.

The Saiph's simulation animation can be checked at:

[From local repository] **Click to video**

[From remote repository] **Click to video**

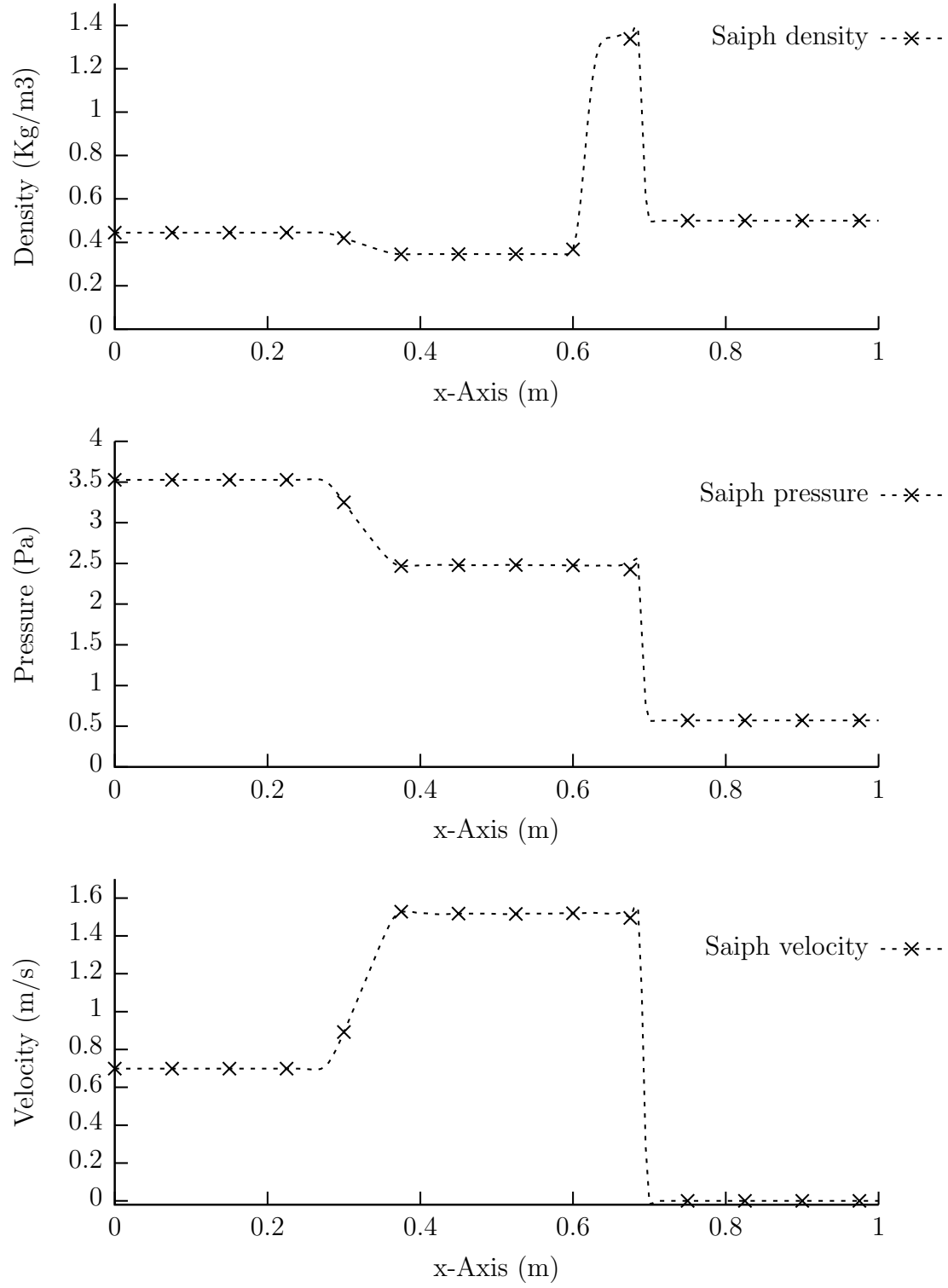


Figure 6: Variable profiles at  $t = 0.08s$  for the Lax Tube problem.

## vi 1D Euler Equations - Shu Osher

A moving shock interacts with sine waves in density. Similar to Sod shock tube use-case with different initial conditions [4].

### Problem Specification

**Use Case.** Shu Osher tube

Spatial domain:  $-5 \leq x < 5$  meters

Governing equations: 1D Euler equations, continuity, momentum, energy and state.

$$\begin{aligned}\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{u}) \\ \frac{\partial(\rho u_i)}{\partial t} &= -\left[ \rho \mathbf{u} \cdot \nabla u_i + u_i \nabla \cdot (\rho \mathbf{u}) + \frac{\partial p}{\partial x_i} \right] \\ \frac{\partial(\rho E)}{\partial t} &= -[\mathbf{u} \cdot \nabla \rho E + \rho E \nabla \cdot \mathbf{u} + \mathbf{u} \cdot \nabla p + p \nabla \cdot \mathbf{u}] \\ p &= (\gamma - 1) \left( (\rho E) - \frac{1}{2} (\rho \mathbf{u}) \mathbf{u} \right)\end{aligned}$$

Initial conditions:

$$\begin{aligned}\gamma &= 1.4 \\ \rho(x) &= \begin{cases} 27/7 \text{ kg/m}^3 & -5 \leq x < -4 \\ 1 + 0.2 \sin(5x) \text{ kg/m}^3 & -4 \leq x \leq 5 \end{cases} \\ \rho \mathbf{u}(x) &= \begin{cases} 10.14185223 \text{ kg/m}^2 \text{s} & -5 \leq x < -4 \\ 0 \text{ kg/m}^2 \text{s} & -4 \leq x \leq 5 \end{cases} \\ p &= \begin{cases} 31/3 \text{ Pa} & -5 \leq x < -4 \\ 1 \text{ Pa} & -4 \leq x \leq 5 \end{cases}\end{aligned}$$

Boundary conditions:

Symmetric boundary condition (Neumann BCs)

$$\begin{aligned}\frac{\partial \rho}{\partial x} &= 0 \text{ kg/m}^4 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases} \\ \frac{\partial(\rho E)}{\partial x} &= 0 \text{ kg/m}^3 \text{s}^2 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases} \\ \frac{\partial(\rho \mathbf{u})}{\partial x} &= 0 \text{ kg/m}^3 \text{s} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases} \\ \frac{\partial p}{\partial x} &= 0 \text{ Pa/m} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}\end{aligned}$$

The Saiph's code specification can be checked at:

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[From remote repository] [Click to Saiph code](#)

## Simulation details

$\Delta x = 25$  mm

$\Delta t = 1$  ms

$nsteps = 1800$

Forward in time integration using 3<sup>rd</sup> order Runke-Kutta method:  $\mathcal{O}(t^3)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

## Results

Output results at final time,  $t = 1.8s$  are presented in Figure 7.

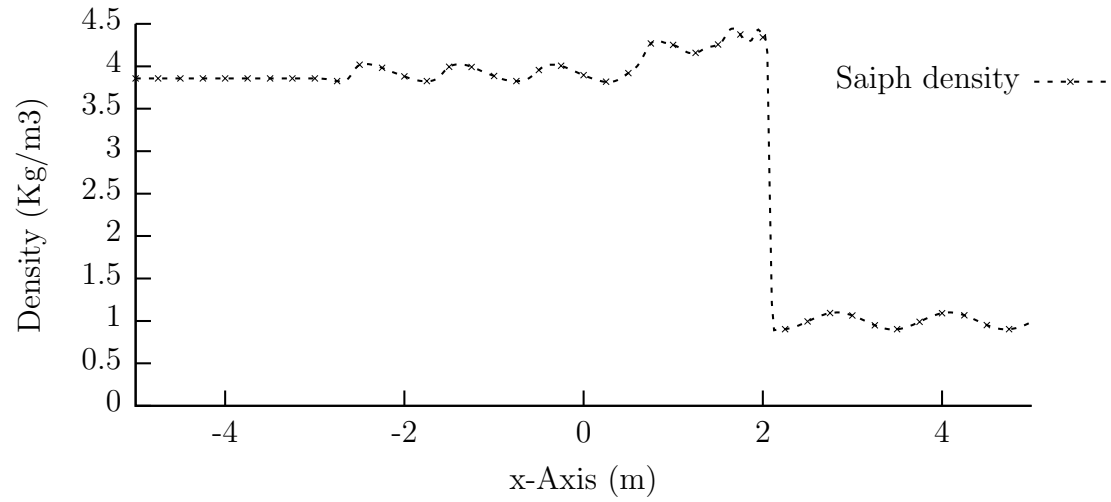


Figure 7: Density profile at  $t = 1.8s$  for the Shu Osher problem.

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

## vii 1D Euler Equations - Sod Shock Tube with Gravitational Force

Similar to Sod shock tube use-case with an uniform gravitational external force  $\mathbf{g}$ .

### Problem Specification

**Use Case.** Sod shock tube

Spatial domain:  $0 \leq x < 1$  meters

Governing equations: 1D Euler equations, continuity, momentum, energy and state with external gravitational force.

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u})$$

$$\frac{\partial(\rho u_i)}{\partial t} = - \left[ \rho \mathbf{u} \cdot \nabla u_i + u_i \nabla \cdot (\rho \mathbf{u}) + \frac{\partial p}{\partial x_i} - \rho g_i \right]$$

$$\frac{\partial(\rho E)}{\partial t} = - [\mathbf{u} \cdot \nabla \rho E + \rho E \nabla \cdot \mathbf{u} + \mathbf{u} \cdot \nabla p + p \nabla \cdot \mathbf{u} - \rho \mathbf{u} \cdot \mathbf{g}]$$

$$p = (\gamma - 1) \left( (\rho E) - \frac{1}{2} (\rho \mathbf{u}) \mathbf{u} \right)$$

Initial conditions:

$$\gamma = 1.4$$

$$\mathbf{g} = 1 \text{ m/s}^2$$

$$\mathbf{u} = 0 \text{ m/s}$$

$$\rho(x) = \begin{cases} 1 \text{ kg/m}^3 & 0 \leq x < 0.5 \\ 0.125 \text{ kg/m}^3 & 0.5 \leq x \leq 1 \end{cases}$$

$$\rho E(x) = \begin{cases} 2.5 \text{ kg/ms}^2 & 0 \leq x < 0.5 \\ 0.25 \text{ kg/ms}^2 & 0.5 \leq x \leq 1 \end{cases}$$

$$p(x) = \begin{cases} 1 \text{ Pa} & 0 \leq x < 0.5 \\ 0.1 \text{ Pa} & 0.5 \leq x \leq 1 \end{cases}$$

Boundary conditions:

Symmetric boundary condition (Neumann BCs) and zero wall velocity (slip-wall BC, Dirichlet BC)

$$\frac{\partial \rho}{\partial x} = 0 \text{ kg/m}^4 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial(\rho E)}{\partial x} = 0 \text{ kg/m}^2 \text{s}^2 \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\rho \mathbf{u} = 0 \text{ kg/m}^3 \text{s} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$

$$\frac{\partial p}{\partial x} = 0 \text{ Pa/m} \quad \begin{cases} x = 0 \text{ m}, \\ x = 1 \text{ m} \end{cases}$$



The Saiph's code specification can be checked at:  
[From local repository]     **Click to Saiph code**  
[From remote repository]   **Click to Saiph code**

## Simulation details

$\Delta x = 2.5$  mm

$\Delta t = 0.2$  ms

$nsteps = 1000$

Forward in-time integration using 3<sup>rd</sup> order Runge-Kutta method:  $\mathcal{O}(t^3)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

## Results

Output results at final time,  $t = 0.2s$  are presented in Figure 8.

The Saiph's simulation animation can be checked at:

[From local repository]     **Click to video**

[From remote repository]   **Click to video**

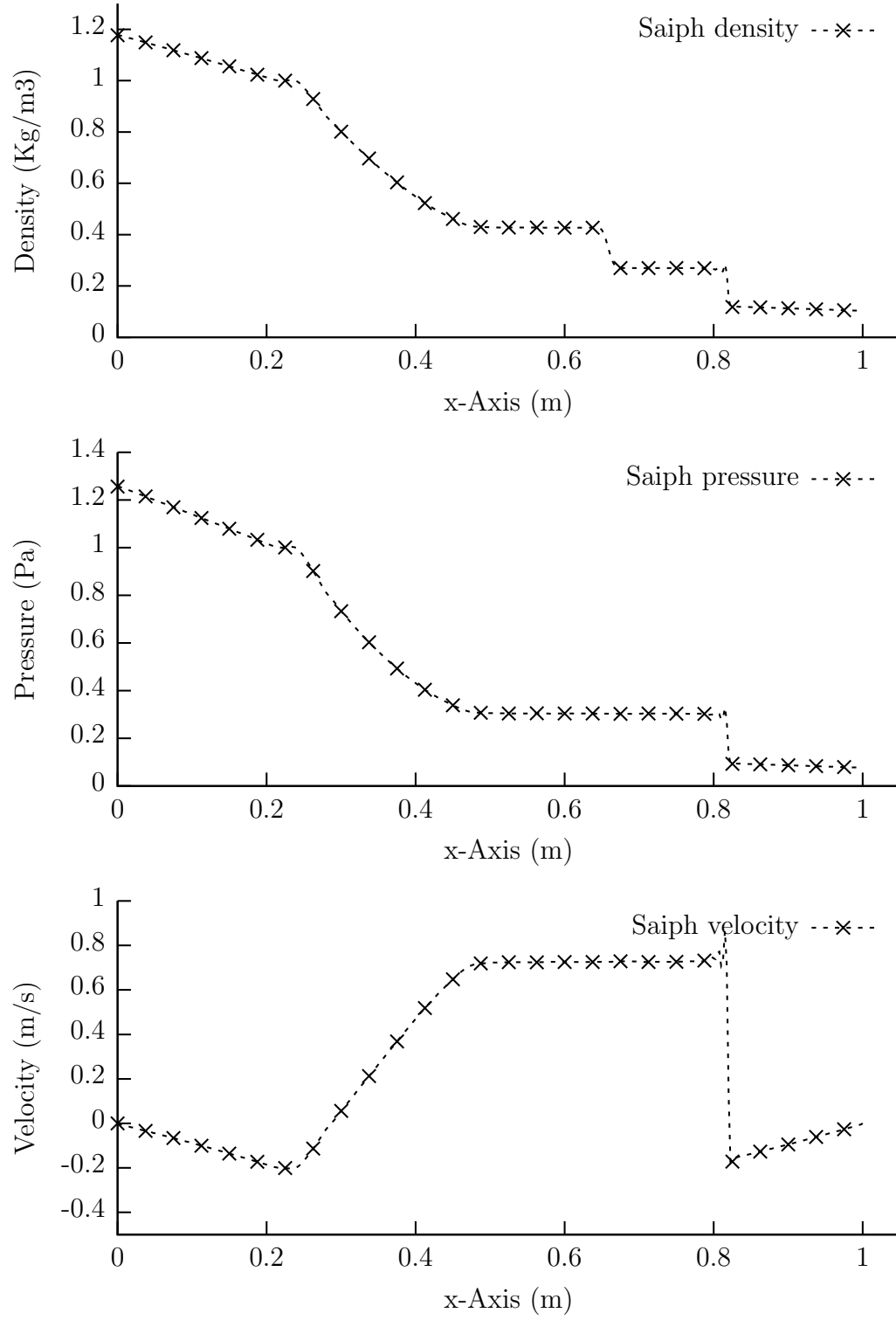


Figure 8: Variable profiles at  $t = 0.2s$  for the Sod Tube problem with gravitational force.

## viii 2D Linear Advection - Gaussian Pulse

### Problem Specification

**Use Case.** Linear Advection

Spatial domain:  $-6 \leq x < 6$  meters,  $-3 \leq y < 3$  meters periodic boundary conditions in both directions

Governing equations: 2D Linear Advection Equation

$$\frac{\partial \phi}{\partial t} = -\mathbf{u} \cdot \nabla \phi$$

Initial conditions:

$$\phi(x) = e^{-\left(\frac{x^2}{2} + \frac{y^2}{2}\right)}$$
$$\mathbf{u} = (1, 0) \text{ m/s}$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

### Simulation details

$\Delta x = 40$  mm

$\Delta t = 40$  ms

$nsteps = 300$

Forward in-time integration using Euler method:  $\mathcal{O}(t)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

### Results

Output results at three time-steps,  $t = 0s$ ,  $t = 6s$  and  $t = 12s$  are presented in Figure 9.

The  $L_2$  norm has been computed over the  $\phi$  variable taking the initial conditions as the analytic solution. The output simulation presents no truncation error  $\mathbf{L}_2 = \mathbf{0}$

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

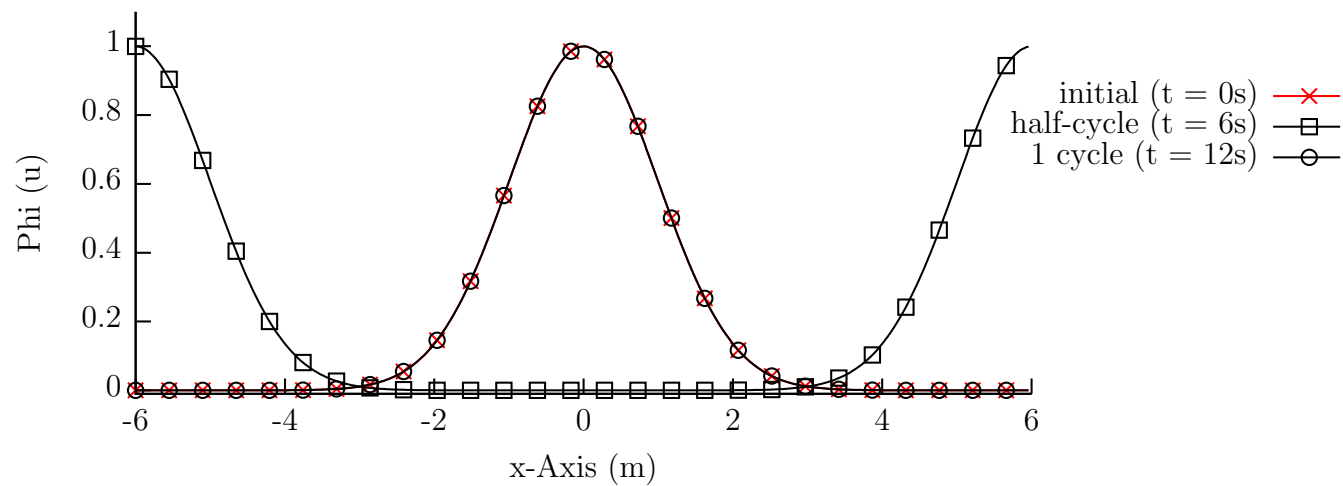


Figure 9:  $\phi(x, y)$  profile at different time-steps.

## ix 2D Linear Diffusion - Sine Wave

### Problem Specification

**Use Case.** Linear Diffusion

Spatial domain:  $0 \leq x, y < 1$  meters, periodic boundary conditions in both directions

Governing equations: 2D Linear Diffusion Equation

$$\frac{\partial \phi}{\partial t} = \nabla \cdot (\nu \nabla \phi)$$

Initial conditions:

$$\phi(x) = \sin(2\pi x) \sin(2\pi y)$$

$$\nu = 0.001 \text{ m}^2/\text{s}$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

### Simulation details

$$\Delta x = 12.5 \text{ mm}$$

$$\Delta t = 20 \text{ ms}$$

$$nsteps = 500$$

Forward in-time integration using 4<sup>th</sup> order Runge-Kutta method:  $\mathcal{O}(t^4)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

### Results

Output results of the  $\phi$  diagonals profiles at three time-steps,  $t = 0s$ ,  $t = 5s$  and  $t = 10s$  are presented in Figure 10.

The  $L_2$  norm has been computed over the  $\phi$  variable taking the analytic solution as reference:

$$\phi(x, t) = e^{-\nu 8\pi^2 t} \sin(2\pi x) \sin(2\pi y)$$

The final output simulation ( $t = 10s$ ), presents an error of  $\mathbf{L_2} = \mathbf{1.04 \cdot 10^{-7}}$

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

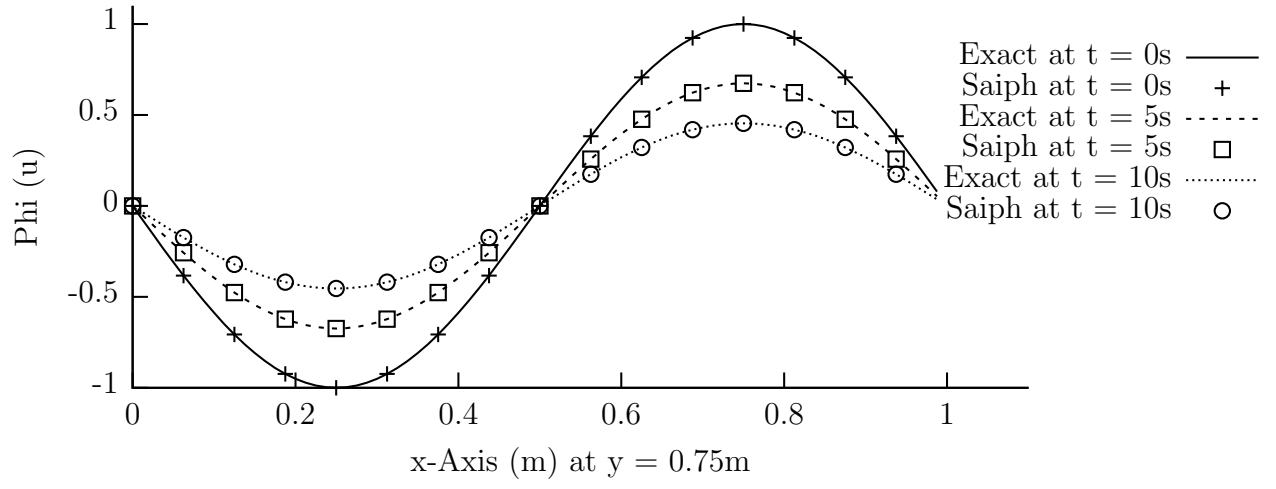


Figure 10: Phi x-profile at different time-steps.

## x 2D Euler Equations - Inviscid Vortex Convection

### Problem Specification

**Use Case.** Inviscid Vortex Convection

Spatial domain:  $0 \leq x, y < 10$  meters, periodic boundary conditions in both directions

Governing equations: 2D Euler Equation

$$\frac{\partial \rho}{\partial t} = -\mathbf{u} \cdot \nabla \rho - \rho \nabla \cdot \mathbf{u}$$

$$\frac{\partial(\rho u_i)}{\partial t} = -\mathbf{u} \cdot \nabla(\rho u_i) - (\rho u_i) \nabla \cdot \mathbf{u} - (\nabla p)_i$$

$$\frac{\partial(\rho E)}{\partial t} = -\mathbf{u} \cdot \nabla(\rho E) - (\rho E) \nabla \cdot \mathbf{u} - \mathbf{u} \cdot \nabla p - p \nabla \cdot \mathbf{u}$$

$$p = (\gamma - 1) \left( \rho E - \frac{1}{2} \rho u^2 \right)$$

Initial conditions:

Adiabatic index  $\gamma = 1.4$

Vortex strength  $b = 0.5$

Vortex initial center  $(x_c, y_c) = (5, 5)$

Distance from the vortex center  $r = [((x - x_c)^2 + (y - y_c)^2)]^{1/2}$

$$\rho = \left[ 1 - \frac{(\gamma - 1)b^2}{8\gamma\pi^2} e^{1-r^2} \right]^{\frac{1}{\gamma-1}}$$

$$u_x = \frac{b}{2\pi} e^{\frac{1}{2}(1-r^2)} (y - y_c)$$

$$u_y = 0.1 - \frac{b}{2\pi} e^{\frac{1}{2}(1-r^2)} (x - x_c)$$

$$p = 1$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

### Simulation details

$\Delta x = 19.53125$  mm

$\Delta t = 3.125$  ms

$nsteps = 3200$

Forward in-time integration using 3<sup>rd</sup> order Runke-Kutta method:  $\mathcal{O}(t^3)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

## Results

Output results at initial time  $t = 0s$  and final  $t = 10s$  are presented in Figure 11. After one convection cycle, the  $L_2$  norm of the pressure quantity, taking the initial conditions as reference results is  $L_2 = 4 \cdot 10^{-6}Pa$ .

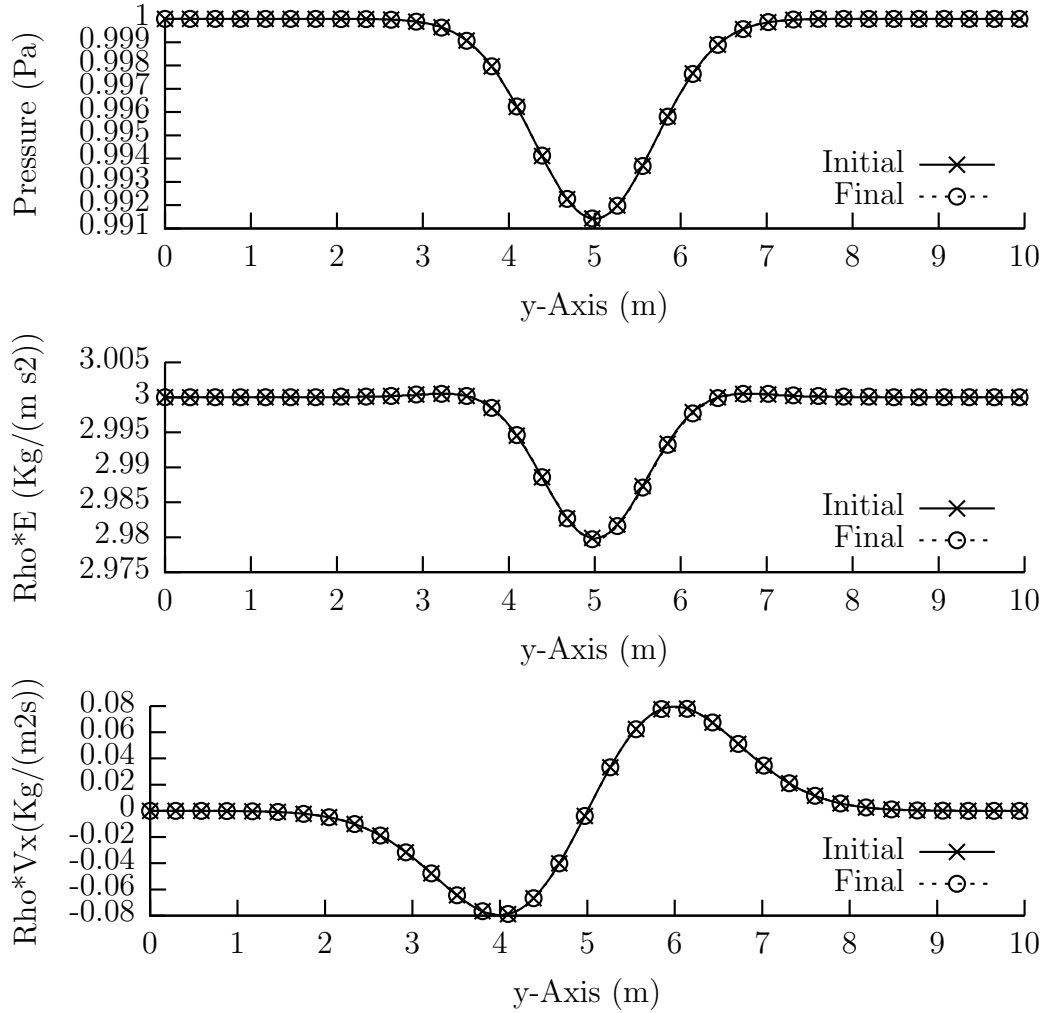


Figure 11: Variable profiles after one convection cycle for the Inviscid Vortex Convection application.

The Saiph's simulation animation can be checked at:

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## xi 2D Non-linear Advection - Smith Hutton

This application corresponds to a specific test problem presented by Smith and Hutton from 1982 [5]. It corresponds to a two-dimensional convection test problem where a scalar field such as  $\phi$  reaches a steady-state in a prescribed velocity field  $\mathbf{u}(x, y)$  with no diffusion. Figure 12 schematizes this test problem.

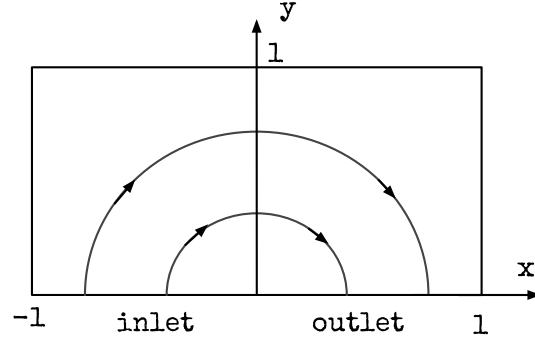


Figure 12: Schema of Smith Hutton problem.

### Problem Specification

**Use Case.** Smith Hutton problem

Spatial domain:  $-1 \leq x < 1$  meters,  $0 \leq y < 1$  meters.

Governing equations: 2D Advection Equation

$$\frac{\partial \phi}{\partial t} = -\mathbf{u} \cdot \nabla \phi - \phi \nabla \cdot \mathbf{u}$$

Initial conditions:

$$\phi = 1 - \tanh(\alpha)$$

$$\mathbf{u} = (2y(1 - x^2), -2x(1 - y^2))m/s$$

Boundary conditions:

Wall inlet and outlet boundary conditions.

$$\begin{aligned} \phi &= 1 + \tanh(\alpha(2x + 1)) & \begin{cases} y = 0 \\ x < 0 \end{cases} & (inlet) \\ \frac{\partial \phi}{\partial y} &= 0 & \begin{cases} y = 0 \\ x \geq 0 \end{cases} & (outlet) \\ \phi &= 1 - \tanh(\alpha) & & elsewhere \end{aligned}$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

## Simulation details

$\Delta x = 10$  mm

$\Delta t = 1$  ms

$nsteps = 3000$

Forward in-time integration using 3<sup>rd</sup> order Runke-Kutta method:  $\mathcal{O}(t^4)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^4)$

## Results

Output results of the  $\phi$  y-profile at  $x = 0m$  and converged stationary state, are presented in Figure 13.

The  $L_2$  norm has been computed over the  $\phi$  variable taking the analytic solution as reference:

$$\phi(x_0, y) = 1 + \tanh(\alpha(1 - 2y))$$

The final output simulation, presents an error of  $\mathbf{L_2 = 9.6 \cdot 10^{-3}}$

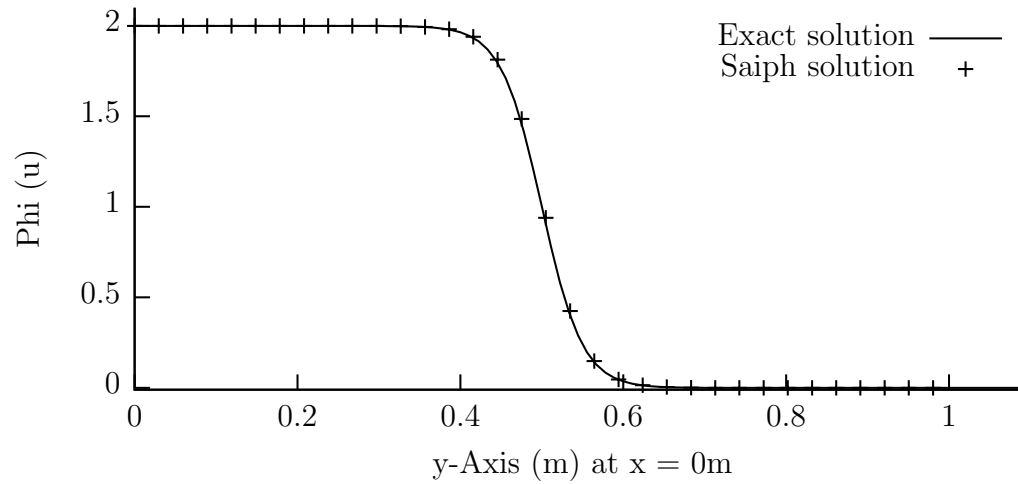


Figure 13: Phi y-profile at  $x = 0m$ , converged state.

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

## xii 2D Euler Equations with gravitational force - Rising Thermal Bubble

The rising thermal bubble application simulates the evolution of a warm bubble in a constant potential temperature environment [1]. The initial bubble is warmer than the ambient air. The air mass is initially at rest and in hydrostatic balance. A potential temperature perturbation is then added, so at  $t_0$  the bubble starts to move up, deforming as a consequence of the shearing motion caused by the velocity field gradients.

### Problem Specification

**Use Case.** Rising Thermal Bubble

Spatial domain:  $0 \leq x < 1000$  meters,  $0 \leq y < 1000$  meters.

Governing equations: 2D Euler Equations in conservative form using density, momentum, and potential temperature.

$$\begin{aligned}\frac{\partial \rho}{\partial t} &= -\mathbf{u} \cdot \nabla \rho - \rho \nabla \cdot \mathbf{u} \\ \frac{\partial(\rho u_i)}{\partial t} &= -\mathbf{u} \cdot \nabla(\rho u_i) - (\rho u_i) \nabla \cdot \mathbf{u} - (\nabla p)_i - \rho g \hat{k}_i \\ \frac{\partial(\rho \theta)}{\partial t} &= -\mathbf{u} \cdot \nabla(\rho \theta) - (\rho \theta) \nabla \cdot \mathbf{u} \\ p &= p_0 \left( \frac{\rho R \theta}{p_0} \right)^{c_p/c_v}\end{aligned}$$

Initial conditions:

Gas constant  $R = c_p - c_v = 287.058 \text{ m}^2/\text{K s}^2$

Specific heats for constant pressure  $c_p = 717.645 \text{ m}^2/\text{K s}^2$

Specific heats for constant volume  $c_v = 1004.703 \text{ m}^2/\text{K s}^2$

Adiabatic index  $\gamma = 1.4$

Gravitational constant  $g = 9.8 \text{ m/s}^2$

Pressure at the surface  $p_0 = 100000 \text{ Pa}$

Directional vector along the vertical  $\hat{k} = (0, 1)$

Mean potential temperature  $\bar{\theta} = 300 \text{ K}$

Exner pressure (hydrostatic balance)  $p_{exner}(y) = 1 - \frac{gy}{c_p \bar{\theta}} \text{ u.a.}$

Perturbation temperature amplitude  $\theta_c = 0.5 \text{ K}$

Perturbation center  $(x_c, y_c) = (500, 350) \text{ m}$

Perturbation radius  $r_c = 250 \text{ m}$

With  $r = \sqrt{(x - x_c)^2 + (y - y_c)^2}$ ,

$$\theta(x, y) = \begin{cases} \bar{\theta} & r > r_c \\ \bar{\theta} + \frac{1}{2}\theta_c(1 + \cos \frac{\pi r}{r_c}) & r \leq r_c \end{cases}$$

$$\rho = \left( \frac{p_0}{R \theta} \right) p_{exner}^{c_v/R}$$

$$\mathbf{u} = (0, 0) \text{ m/s}$$

$$p = p_0 \left( \frac{\rho R \theta}{p_0} \right)^{c_p/c_v}$$

The Saiph's code specification can be checked at:

[From local repository] [Click to Saiph code](#)

[From remote repository] [Click to Saiph code](#)

## Simulation details

$\Delta x = 20$  m

$\Delta t = 5$  ms

$nsteps = 14000$

Forward in-time integration using 3<sup>rd</sup> order Runke-Kutta method:  $\mathcal{O}(t^4)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^3)$

## Results

The following plots shows the potential temperature perturbation  $d\theta = \frac{\rho\theta}{\rho} - \bar{\theta}$  at the initial and final time  $t = 0 - 700s$ .

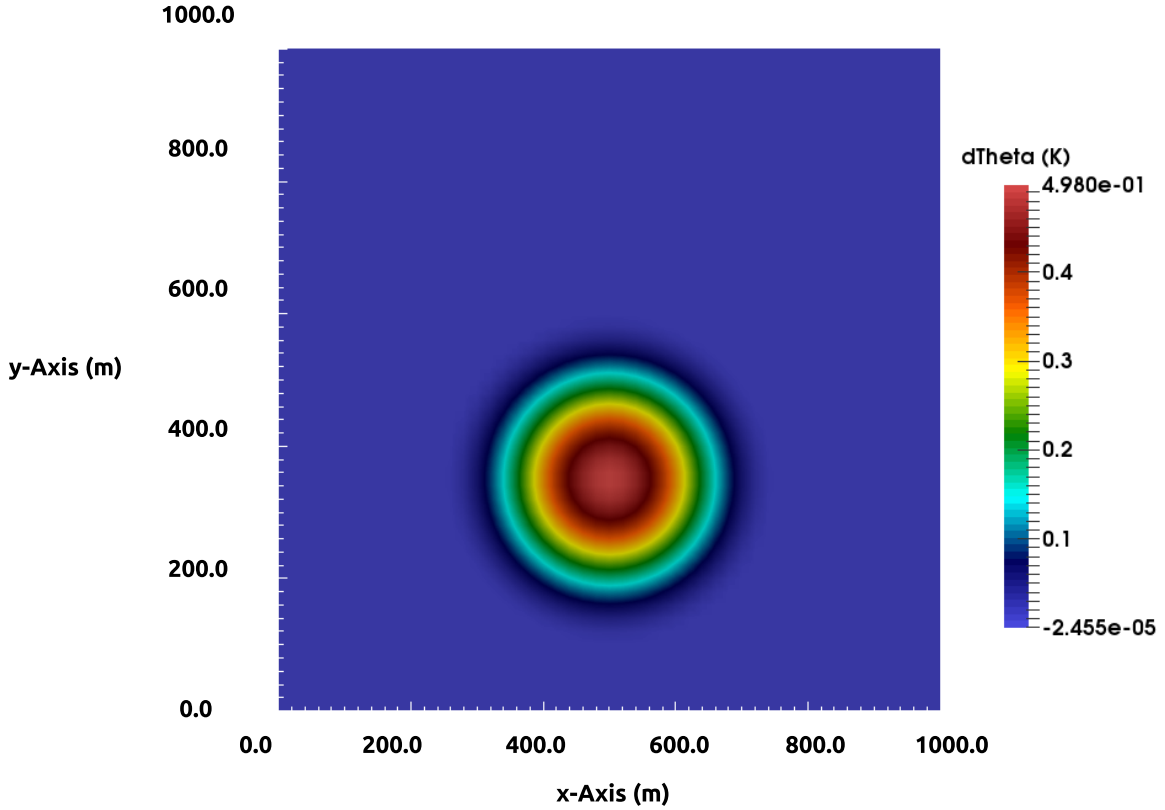


Figure 14: Potential temperature perturbation at  $t = 0s$ .

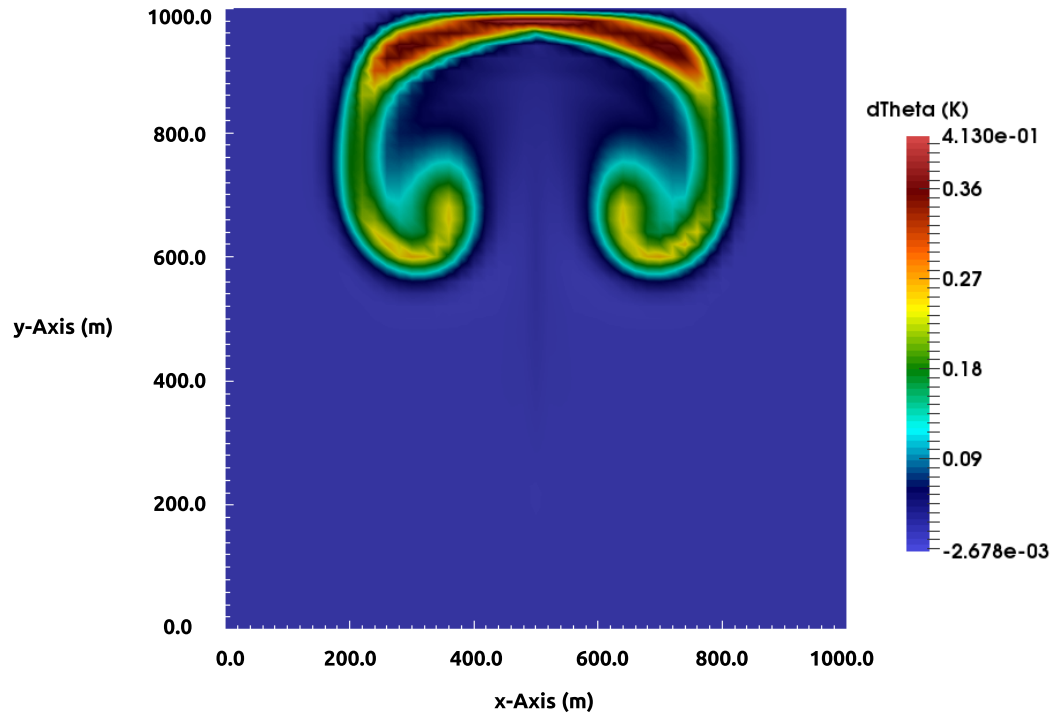


Figure 15: Potential temperature perturbation at  $t = 700s$ .

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)

## xiii 2D Taylor-Green Vortex

This application is a simplification of the test problem presented by Taylor and Green in 1937 [7]. It corresponds to a two-dimensional unsteady flow of a decaying vortex.

### Problem Specification

**Use Case.** Taylor-Green vortex

Spatial domain:  $-\pi L \leq x, y \leq \pi L$ , with  $\pi L = 0.016$  meters, periodic boundary conditions in both directions.

Governing equations: 2D Navier-Stokes

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\mathbf{u}\rho) \quad (1)$$

$$\frac{\partial (\rho u)_i}{\partial t} = -\nabla \cdot ((\rho u)_i \cdot \mathbf{u} + p) + \mu \nabla^2 u_i \quad (2)$$

$$\frac{\partial (\rho E)}{\partial t} = -\nabla \cdot ((\rho E) \cdot \mathbf{u} + p \cdot \mathbf{u}) + \mu (u_x \nabla^2 u_x + u_y \nabla^2 u_y) + \frac{\mu c_p}{Pr} \nabla^2 T \quad (3)$$

$$p = \rho R T, \text{ with } T = \frac{1}{c_v} \left( \frac{\rho E}{\rho} - \frac{1}{2} \mathbf{u} \cdot \mathbf{u} \right) \quad (4)$$

For simulation output purposes we compute the fluid vorticity quantity:

$$\omega = \frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y} \quad (5)$$

Initial conditions:

#### Initial flow fields

Density  $\rho = \frac{p}{RT}$

Velocity  $\mathbf{u} = \begin{cases} u_x = U_0 \sin \frac{x}{L} \cos \frac{y}{L} \\ u_y = -U_0 \cos \frac{x}{L} \sin \frac{y}{L} \end{cases}$

Pressure  $p = p_0 + \frac{3\rho_0 U_0^2}{16} \left( \cos \frac{2x}{L} + \cos \frac{2y}{L} \right)$

Temperature  $T = T_0$

#### Initial flow parameters

Initial velocity value  $U_0 = 33.7 \text{ m/s}$

Initial temperature  $T_0 = 273 \text{ K}$

Initial density  $\rho_0 = 194.60 \cdot 10^{-3} \text{ kg/m}^3$

Initial pressure  $p_0 = \rho_0 R T_0 = 15778.49 \text{ Pa}$

Gas constant for nitrogen  $R = 297 \text{ J/(kgK)}$

Mach number for the ICs  $Ma = \frac{U_0}{c_{so}} = 0.1$

Speed of sound for nitrogen (at the initial temperature)  $c_{so} = \sqrt{\gamma R T_0}$

Specific heat ratio  $\gamma = \frac{c_p}{c_v} = 1.4$

Reynolds number  $Re = \frac{\rho_0 U_0 L}{\mu_0} = 2000$

Dynamic shear viscosity for nitrogen (at the initial temperature)  $\mu_0 = 1.67 \cdot 10^{-5} kg/(ms)$   
 Prandtl number  $Pr = 0.71$   
 Convective time scale  $t_c = \frac{L}{U_0} = 1.5 \cdot 10^{-4} s$

The Saiph's code specification can be checked at:  
 [From local repository] [Click to Saiph code](#)  
 [From remote repository] [Click to Saiph code](#)

## Simulation details

$$\Delta x = 8 \cdot 10^{-5} \text{ m}$$

$$\Delta t = 7,6 \cdot 10^{-7} \text{ s}$$

$$nsteps = 800000$$

Forward in-time integration using 3<sup>rd</sup> order Runke-Kutta method:  $\mathcal{O}(t^3)$

Spatial differentiation accuracy (default):  $\mathcal{O}(x^8)$

## Results

The problem has a time-dependent analytical solution derived from the incompressible two-dimensional stream function [3].

We compare Saiph numerical output results with the time-dependent analytical solution given in terms of the vorticity as  $\omega = \omega_{init} e^{-\frac{2}{Re} \frac{t}{t_c}}$ .

Figure 16 shows the vorticity contours of the Saiph simulation.

Finally, the  $L_2$  norm has been computed over the  $\omega$  variable taking the analytic solution as reference. Figure 17 reports the errors obtained.

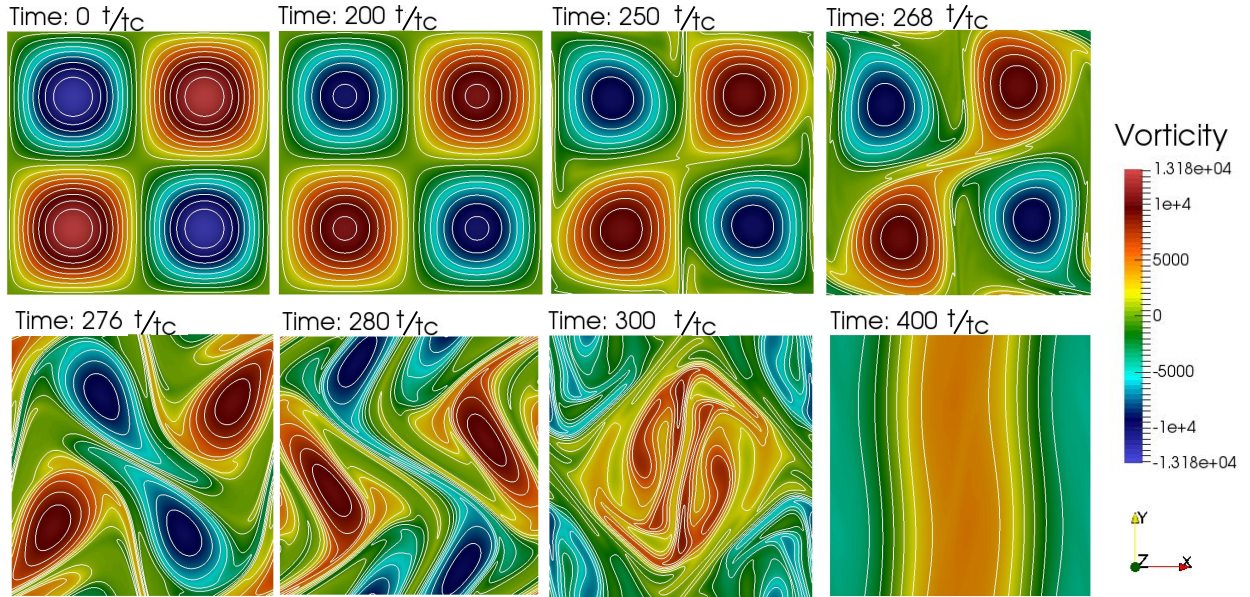


Figure 16: Saiph 2D-TGV vorticity contours at different time-steps using a RK3 time-integration method in a  $400 \times 400$  mesh at  $Re = 2000$

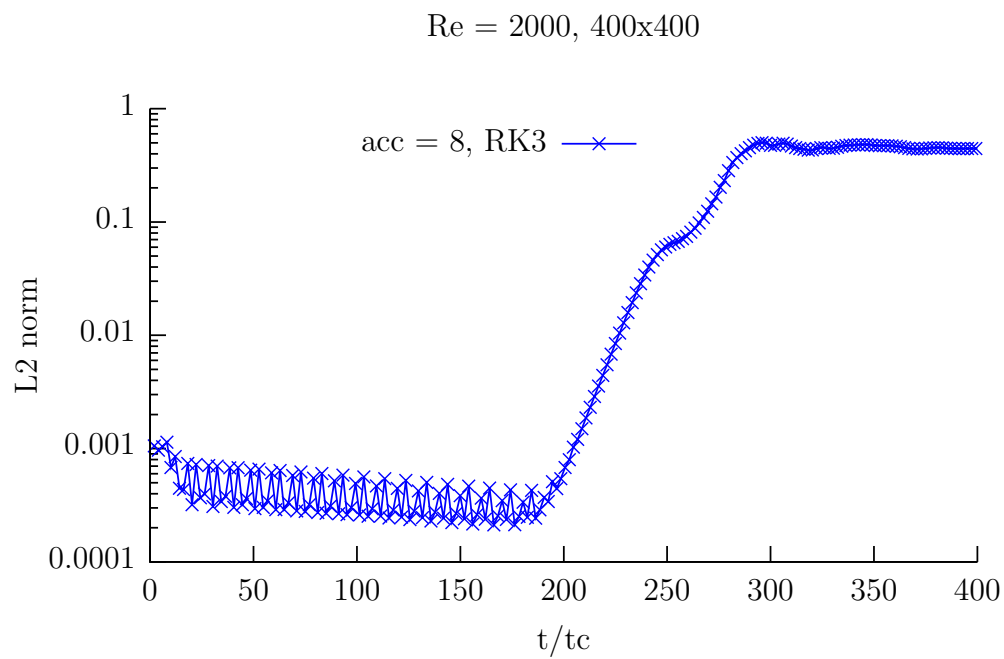


Figure 17: Saiph 2D-TGV vorticity L2 norm

The Saiph's simulation animation can be checked at:

[From local repository] [Click to video](#)

[From remote repository] [Click to video](#)



## References

- [1] GIRALDO, F. X., AND RESTELLI, M. A study of spectral element and discontinuous galerkin methods for the navier–stokes equations in nonhydrostatic mesoscale atmospheric modeling: Equation sets and test cases. *Journal of Computational Physics* 227, 8 (2008), 3849–3877.
- [2] MACIÀ, S., MATEO, S., MARTÍNEZ-FERRER, P. J., BELTRAN, V., MIRA, D., AND AYGUADÉ, E. Saiph: Towards a dsl for high-performance computational fluid dynamics. In *Proceedings of the Real World Domain Specific Languages Workshop 2018* (2018), ACM, p. 6.
- [3] SHARMA, N., AND SENGUPTA. Non-linear instability analysis of the two-dimensional navier-stokes equation: The taylor-green vortex problem. *Physics of Fluids* 30 (05 2018), 054105.
- [4] SHU, C.-W., AND OSHER, S. Efficient implementation of essentially non-oscillatory shock-capturing schemes. *Journal of computational physics* 77, 2 (1988), 439–471.
- [5] SMITH, R., AND HUTTON, A. The numerical treatment of advection: A performance comparison of current methods. *Numerical Heat Transfer, Part A Applications* 5, 4 (1982), 439–461.
- [6] SOD, G. A survey of several finite difference methods for systems of nonlinear hyperbolic conservation laws. *Journal of Computational Physics* 27, 1 (1978), 1–31.
- [7] TAYLOR, G. I. S., AND GREEN, A. E. Mechanism of the production of small eddies from large ones. *Proceedings of The Royal Society A: Mathematical, Physical and Engineering Sciences* 158 (1937), 499–521.