A ALE Finite Element Method for Vorticity-Streamfunction Formulation with Species Transport Equation

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June, 17th 2020

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Outline

1. Introduction
2. Mathematical Model
3. Validation
4. Results
5. Conclusion

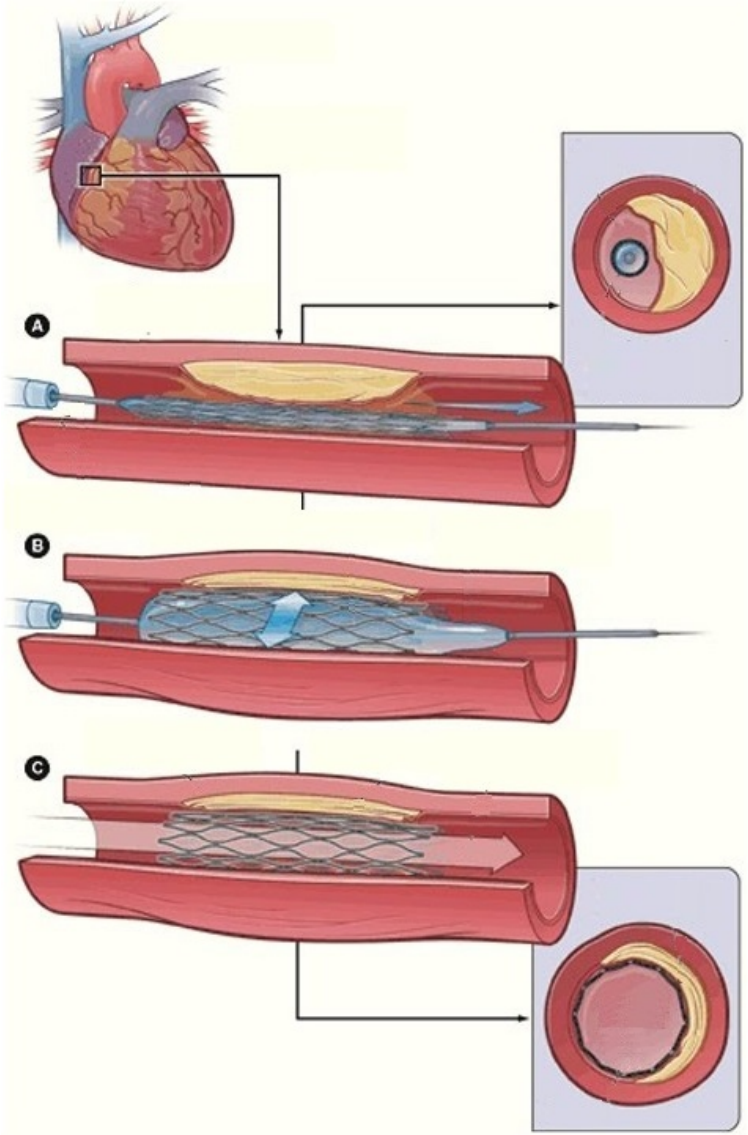
Introduction

Motivation:

- Ischaemic heart disease and stroke have remained the leading death causes globally in the last 15 years [1]

Aims:

- To develop a Finite Element code for stream-vorticity formulation with species transport equation using the Arbitrary Lagrangian-Eulerian (ALE) approach
- To create new drug-eluting design patent



[1] World Health Organization, 2018, "The top 10 causes of death". *www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death* [Online accessed 06-04-20 08:27pm]

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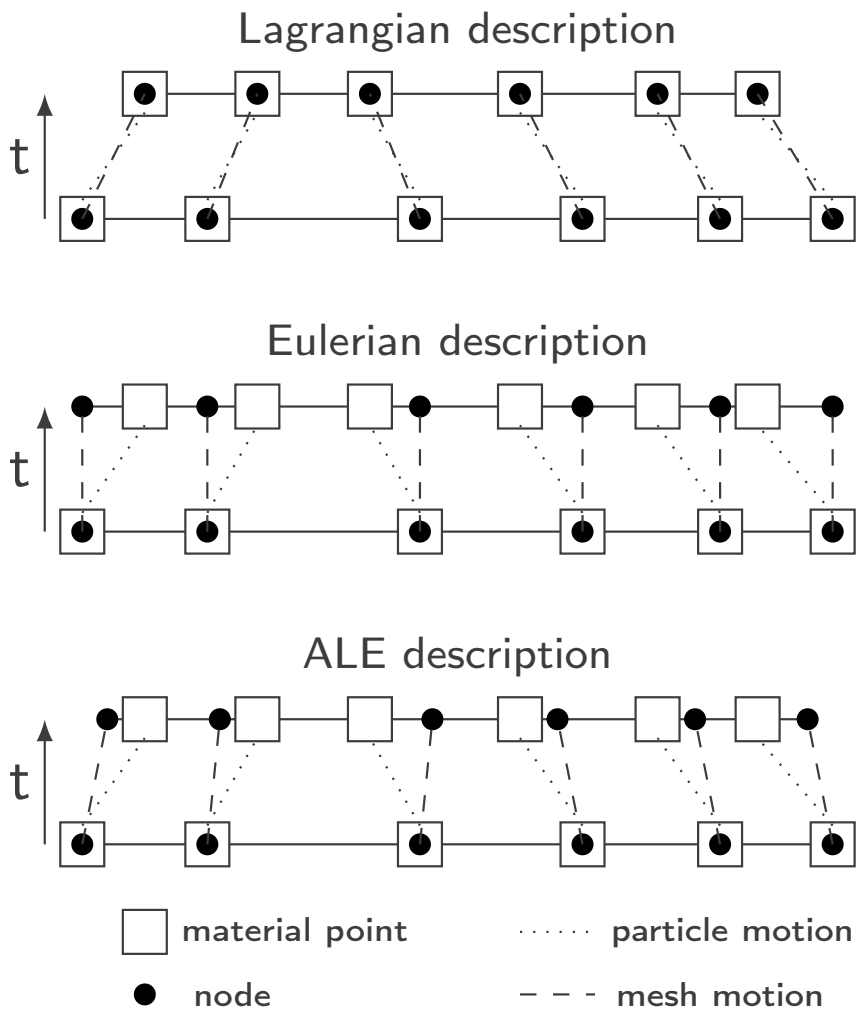
Arbitrary Lagrangian-Eulerian (ALE)

In ALE description, the referential frame moves with an arbitrary velocity that does not necessary represents the Lagrangian or Eulerian description.

The convection velocity is calculated by the relative velocity between the material and the mesh velocity respectively [2]



[2] Donea, J., Huerta, A., Ponthot, J.-P. and Rodríguez-Ferran, A. (2004). Arbitrary Lagrangian–Eulerian Methods. In Encyclopedia of Computational Mechanics *doi:10.1002/0470091355.ecm009*

Governing Equations

1. Continuum hypothesis
2. Homogeneous and Isotropic
3. Incompressible
4. Newtonian
5. Constant Mass Difusivity
6. Single-phase Flow
7. Two-dimensional flow

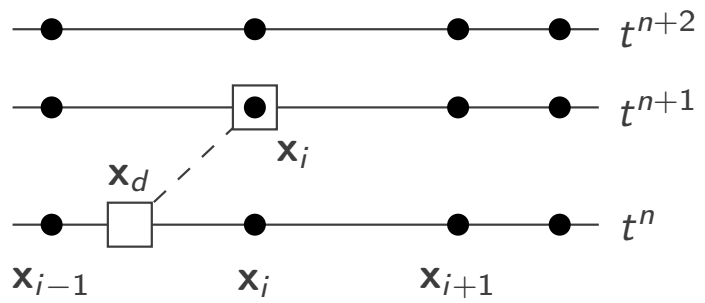
$$\frac{D\omega}{Dt} = \frac{1}{Re}\nabla^2\omega \qquad \nabla^2\psi = -\omega$$

$$\frac{Dc}{Dt} = \frac{1}{ReSc}\nabla^2 c$$

where, $D(\cdot)/Dt$ is substantive derivative and the material velocity field is calculated by: $v_x = \partial\psi/\partial y$ and $v_y = -\partial\psi/\partial x$

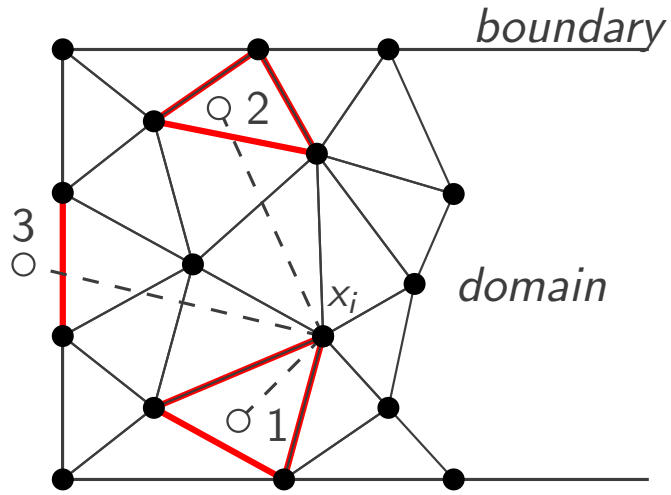
Semi-Lagragian Method

The figure (a) shows 1D space scheme of the semi-Lagrangian method. The departure node is found by integration the mesh backward in time using x_{i-1} and x_i



(a)

The figure (b) shows three possible trajectories of departure node while developing the searching procedure



(b)

Semi-Lagrangian Method

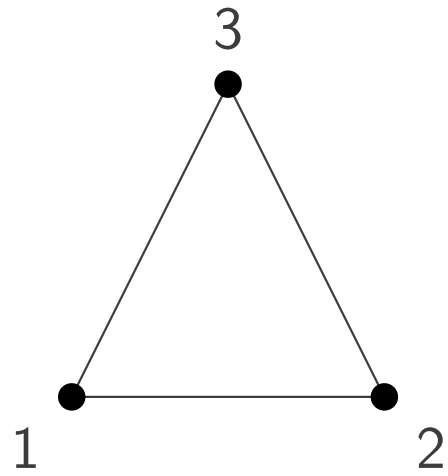
Therefore, the Governing Equations were discretized in time using semi-Lagrangian Method [3]:

$$\frac{\omega_i^{n+1} - \omega_d^n}{\Delta t} = \frac{1}{Re}\nabla^2\omega^{n+1} \qquad \nabla^2\psi = -\omega$$

$$\frac{c_i^{n+1} - c_d^n}{\Delta t} = \frac{1}{ReSc}\nabla^2 c^{n+1}$$

[3] Pironneau, O. On the transport-diffusion algorithm and its applications to the Navier-Stokes equations. Numer. Math. 38, 309–332 (1982). *https://doi.org/10.1007/BF01396435*

Finite Element Method



$$N_i = L_i$$

$$i = 1, 2, 3$$

$$\left[\frac{\mathbf{M}}{\Delta t} + \frac{\mathbf{K}}{Re}\right] \omega_i^{n+1} = \frac{\mathbf{M}}{\Delta t}\omega_d^n \qquad \mathbf{K}\psi = \mathbf{M}\omega$$

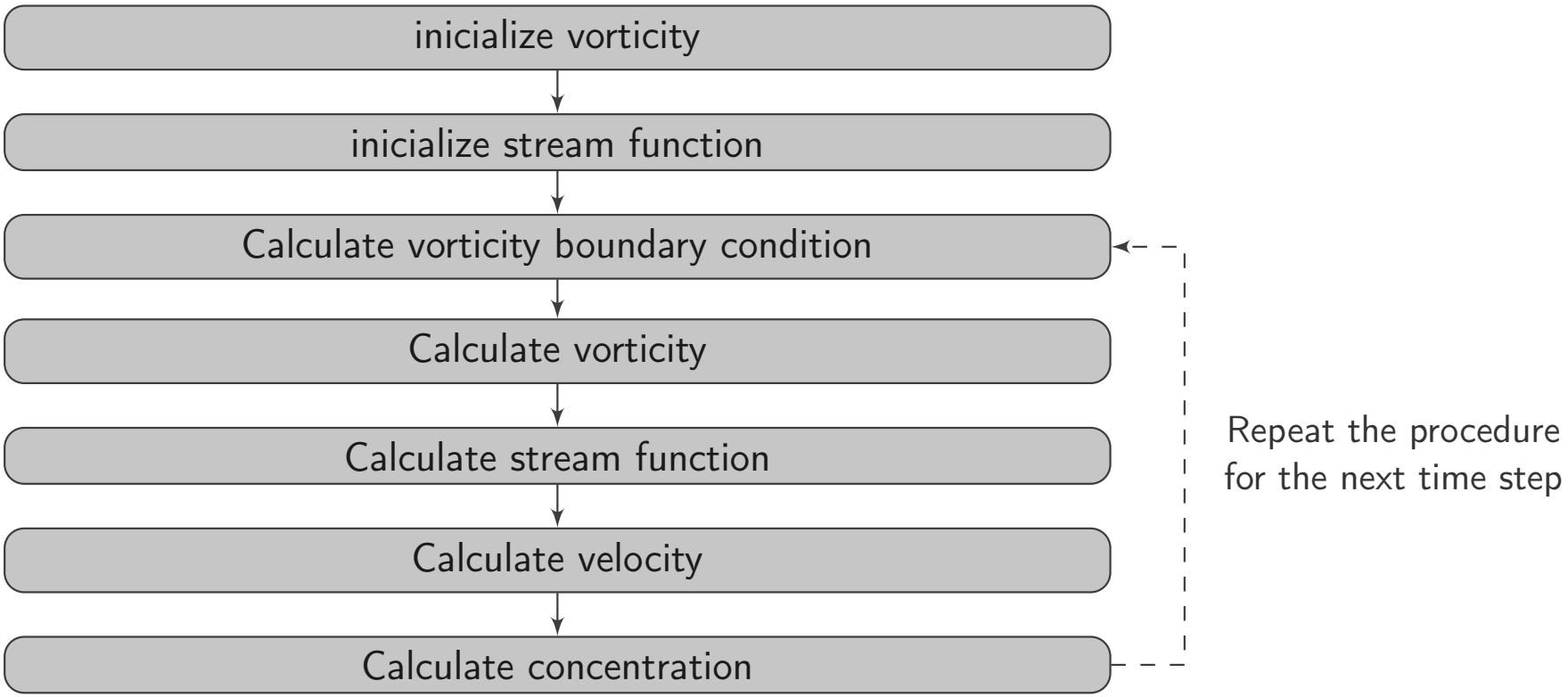
$$\left[\frac{\mathbf{M}}{\Delta t} + \frac{\mathbf{K}}{ReSc}\right] c_i^{n+1} = \frac{\mathbf{M}}{\Delta t} c_d^n$$

The material velocity field is calculated by: $\mathbf{M}v_x = \mathbf{G_y}\psi$ and $\mathbf{M}v_y = -\mathbf{G_x}\psi$

Adaptive Mesh Refinement

Laplace Smoothing description, comparative figures and ALE velocity formula

Solution Algorithm



Streamfunction-Vorticity formulation with species transport equation solution algorithm

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Validation - Poiseuille Flow

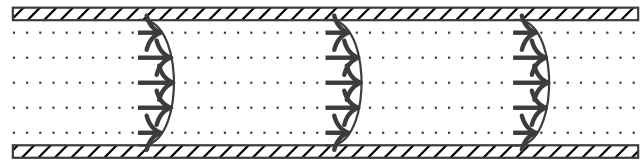
Boundaries Conditions:

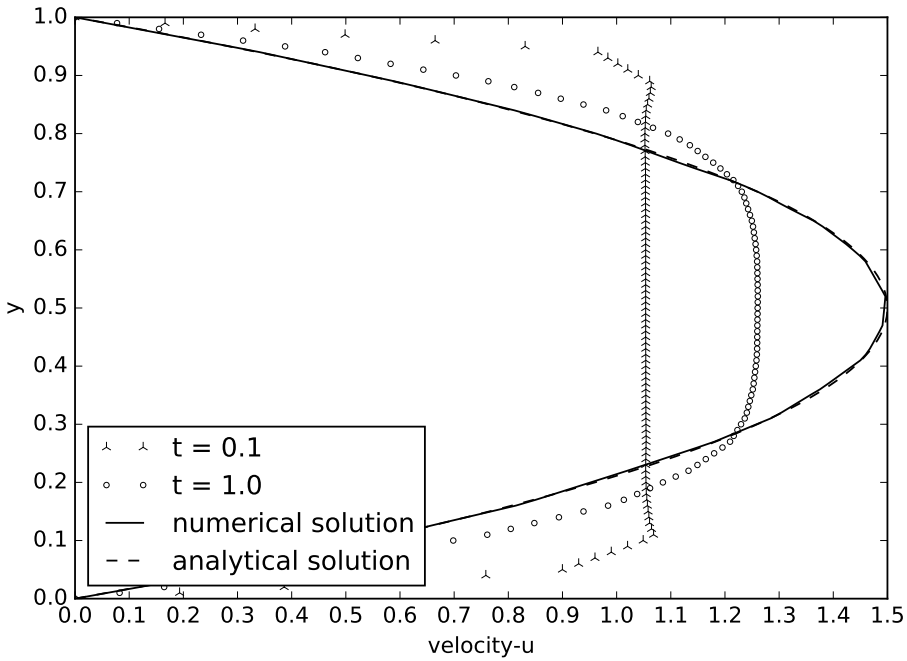
Inflow condition: $u = 1$, $v = 0$ e $\psi = y$

Outflow condition: $\psi = y$

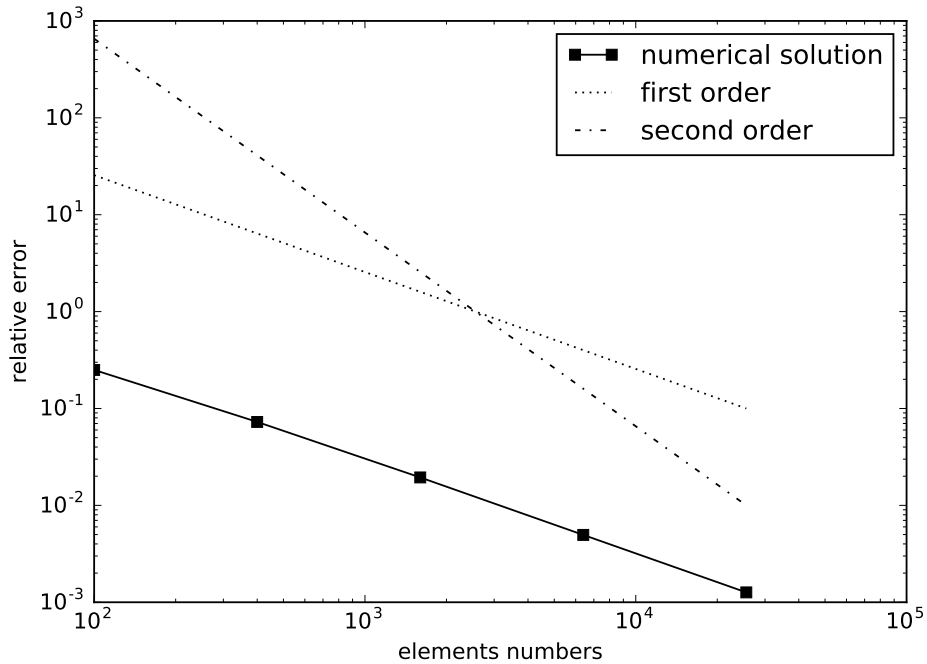
Top plate: $u = 0$, $v = 0$, $\psi = 1$

Bottom plate: $u = 0$, $v = 0$, $\psi = 0$





(a)



(b)

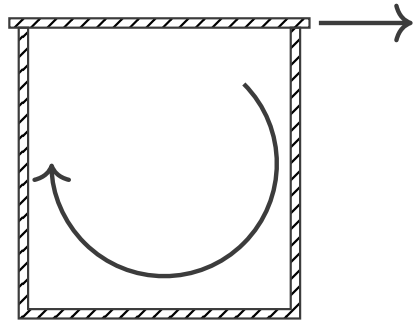
(a) comparison of Poiseuille Flow velocity profile and
(b) log scale graph of convergence order.

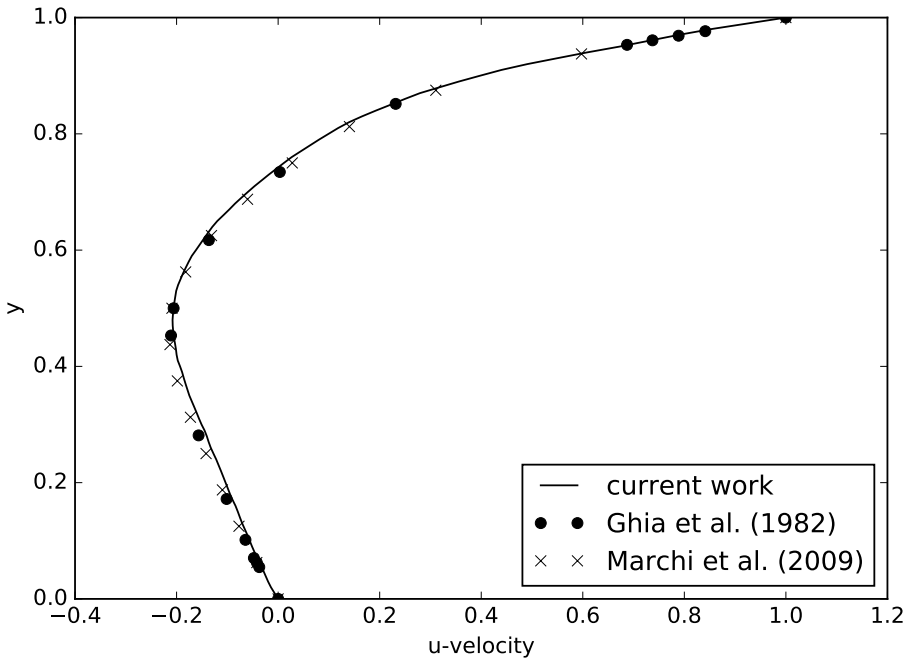
Validation - Lid Driven Cavity Flow

Boundaries Conditions:

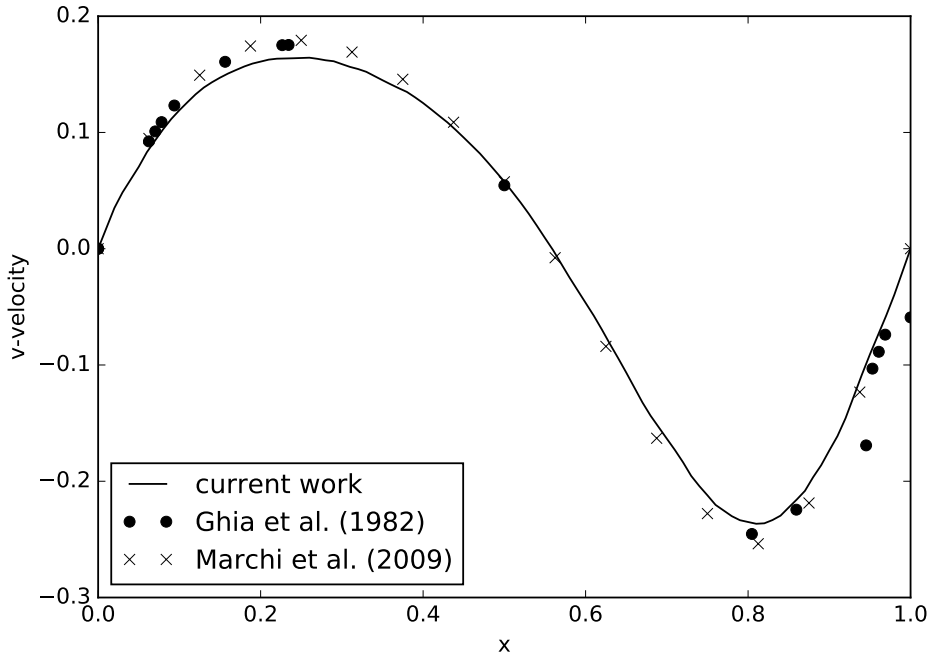
Bottom and side plates: $u = 0$, $v = 0$ e $\psi = 0$

Top plate: $u = 1$, $v = 0$ e $\psi = 0$





(a)



(b)

Centerline velocity profile in a lid-driven cavity for $Re = 100$:
(a) u-velocity and (b) v-velocity.

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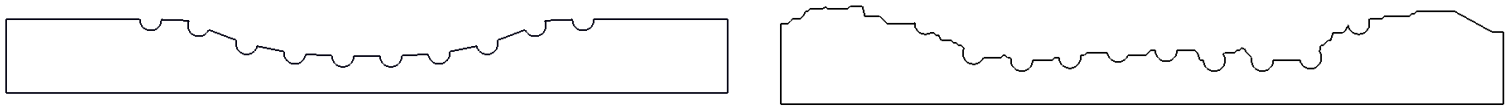
Results



(a) (b)

Non-dimensional symmetric geometry for blood flow in coronary artery with drug-eluting stent placed by Wang et al. (2017): (a) Curved Channel with Stent (b) Real Channel with Stent.

Boundaries Conditions:

Inflow condition: $u = 1$, $v = 0$ e $\psi = y$;

Outflow condition: $\psi = y$;

Top plate: $u = 0$, $v = 0$, $\psi = 1$;

Symmetry condition: $v = 0$, $\psi = 0$;

Drug-eluting stent: $u = 0$, $v = 0$, $\psi = 1$ e $c = 1$

$R = 0.0015m$

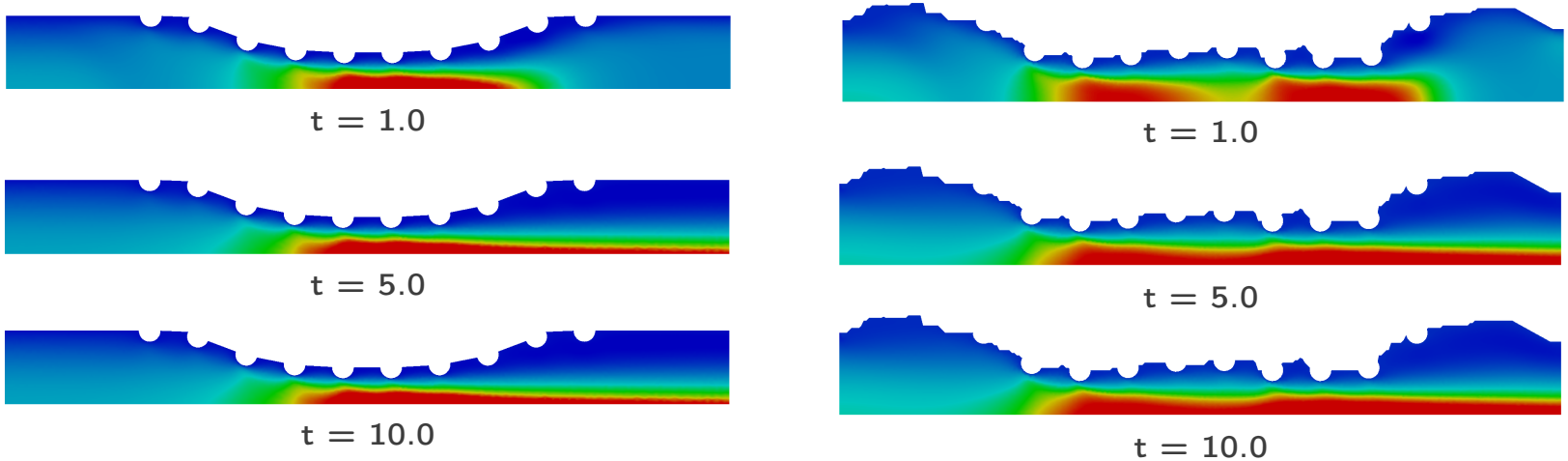
$\mu = 0.0035Pa.s$

$\rho = 1060kg/m^3$

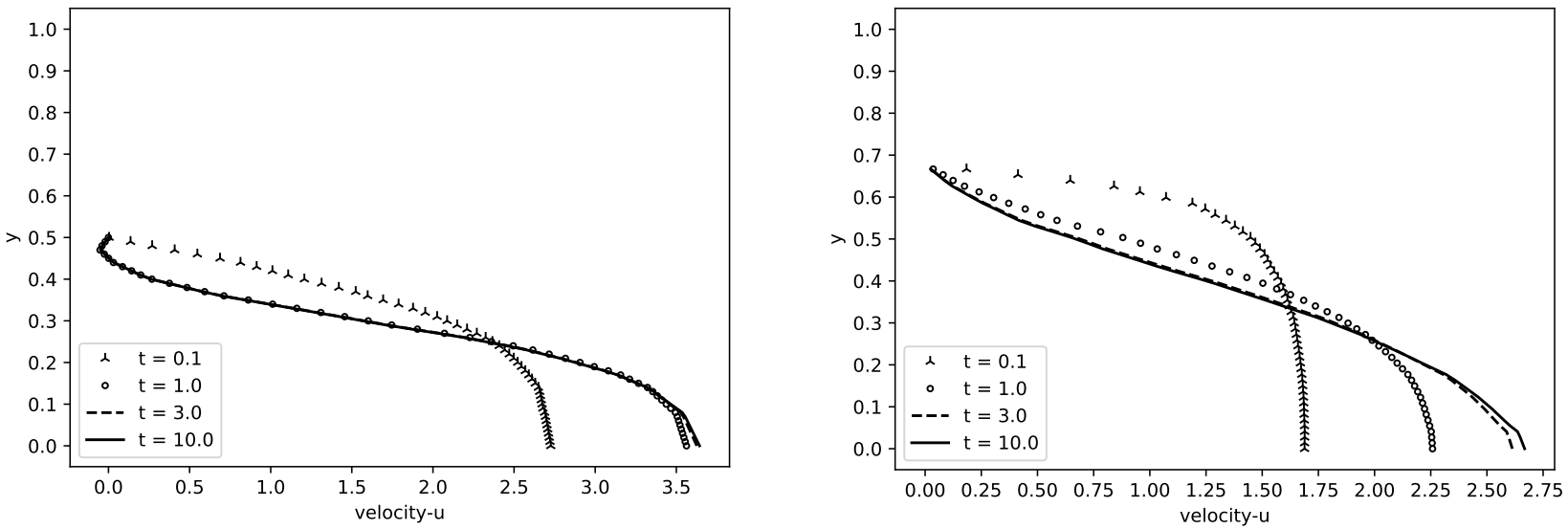
$u = 12cm/s$

$Re = 54.5$

Results - Velocity Field

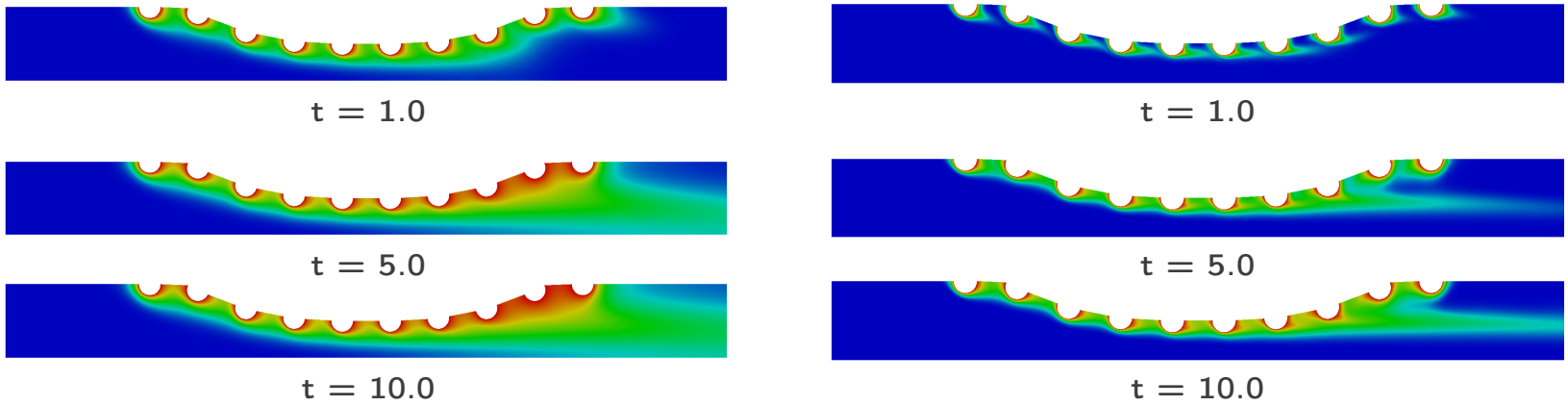


Evolution in time and space of velocity field:
Curved Channel (left column) and Real Channel (right column)

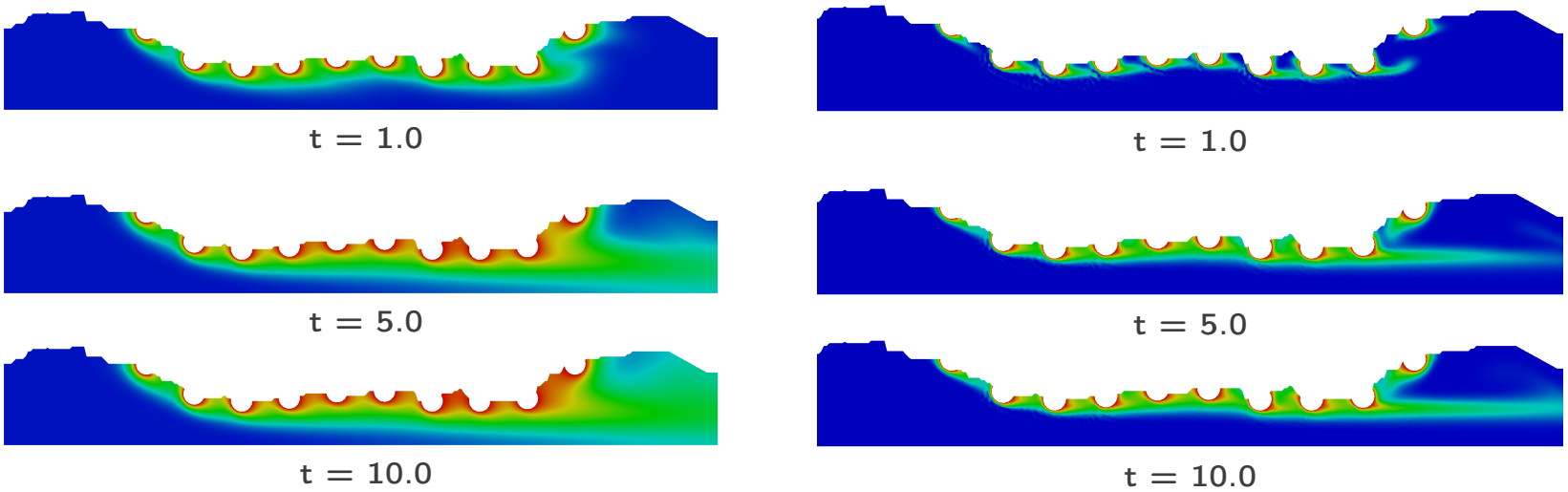


Evolution of velocity profile in centerline ($x = 0.5L$):
(a) Curved Channel and (b) Real Channel

Results - Concentration Field



Evolution in time and space of concentration field in Curved Channel:
$Sc = 1$ (left column) and $Sc = 10$ (right column)



Evolution in time and space of concentration field in Real Channel:
$Sc = 1$ (left column) and $Sc = 10$ (right column)

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Conclusion

1. Was observed that the species transport in blood flow is directly influenced by drug used in stent production

2. The streamfunction-vorticity formulation showed an useful approach for to calculate the velocity and concentration fields since the variables are scalars allowing a smooth implementation

3. Due to generalized construction of the code, the simulator is able to describe drug-eluting stent problem in coronary artery as well as flows of Newtonian fluids with scalar transport (concentration or temperature)

Thank you!

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The authors thank the FAPERJ (Research Support Foundation of the State of Rio de Janeiro) for its financial support