

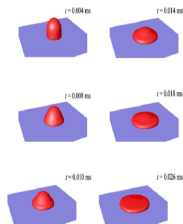
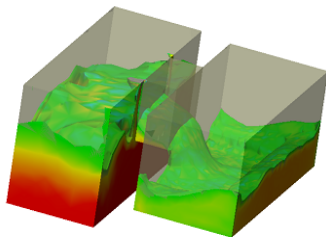
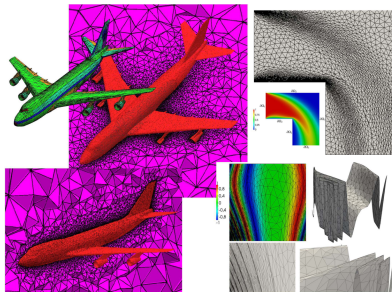
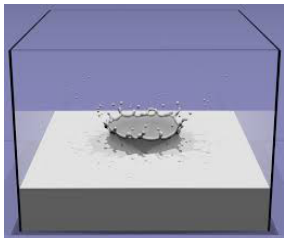
Mecânica de Fluidos Computacional

Roberto F. Ausas

ICMC/USP

Maio 2019



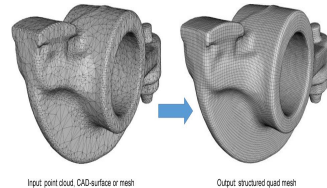
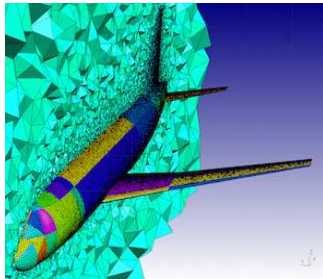
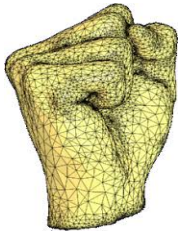


Existem três fases bem diferenciadas na resolução de um problema de mecânica computacional, seja CFD ou CSM:

- **Pré-processo:**
Discretização espacial do domínio computacional
- **Resolução do problema:**
Aplicação de algum método numérico para resolver as equações governantes
- **Pós-processo:**
Visualização e análise da solução obtida

Pré-processo

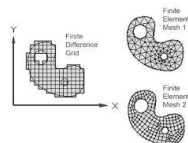
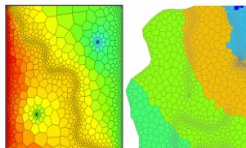
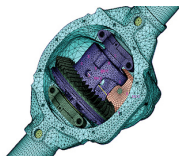
- Geometria computacional, CAD
- Geração de malhas
- Imposição de restrições e condições iniciais



Resolução do problema

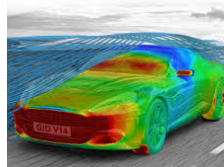
Existem distintos de métodos:

- **Elementos finitos** → Formulação variacionais
- **Volumes finitos** → Leis de conservação
- **Diferenças finitas:** Aproximação de operadores de derivadas por diferenças
- **Outros:** Métodos de partículas, Lattice Boltzmann, etc.



Pós-processo:

- Visualização
- Big Data
- Processamento visual e geométrico
- Realidade virtual



Equações governantes: Navier-Stokes

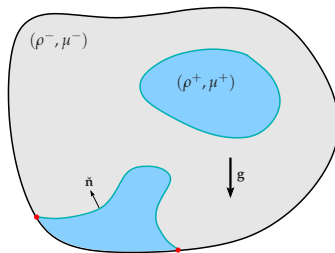
We seek a velocity field $\mathbf{u} \in [H^1(\Omega)]^d$ and a pressure $p \in L^2(\Omega)$ satisfying

$$\left\{ \begin{array}{ll} \rho (\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u}) - \nabla \cdot (2\mu \mathbf{D}(\mathbf{u})) + \nabla p = \mathbf{f} & \text{in } \Omega \setminus \Gamma(t) \\ \nabla \cdot \mathbf{u} = 0 & \text{in } \Omega \\ \mathbf{u} = \mathbf{g} & \text{on } \Gamma_D \\ \llbracket \boldsymbol{\sigma} \rrbracket \cdot \hat{\mathbf{n}} = \mathbf{f}_\Gamma & \text{on } \Gamma(t), \end{array} \right.$$

where

- $\boldsymbol{\sigma}$ é o tensor de tensões;
- (ρ, μ) são a densidade e viscosidade do fluido:

$$(\rho(\mathbf{x}), \mu(\mathbf{x})) = \begin{cases} (\rho^+, \mu^+) & \text{if } \mathbf{x} \in \Omega^+ \\ (\rho^-, \mu^-) & \text{if } \mathbf{x} \in \Omega^- \end{cases}$$



$$\Omega = \Omega^+ \cup \Omega^- \cup \Gamma$$

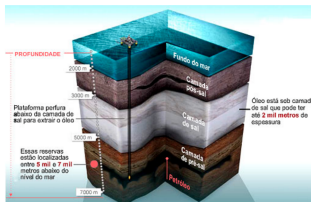
Casos particulares

Darcy problem (Elliptic): Given f and B.C., find \mathbf{u} and p , such that

$$\begin{cases} \nabla \cdot \mathbf{u} = F & \text{in } \Omega \\ \mathbf{u} = -K_r(S) \nabla p & \text{in } \Omega \\ K_r(S) = K \left[\frac{S^2}{\mu_o} + \frac{(1-S)^2}{\mu_w} \right] \\ + \text{B.C.} \end{cases}$$

Transport problem (Hiperbolic): Given \mathbf{u} , find the saturation S , such that

$$\begin{cases} \frac{\partial S}{\partial t} + \nabla \cdot (\varphi(S) \mathbf{u}) = 0 & \text{in } \Omega \\ \varphi(S) = \frac{MS^2}{MS^2 + (1-S)^2} \\ S(\mathbf{x}, 0) = S_0 & \text{in } \Omega \\ S(\mathbf{x}, t) = S_D & \text{se } \mathbf{u} \cdot \mathbf{n} < 0 \text{ in } \partial\Omega \end{cases}$$



Reynolds equation + cavitation \rightarrow The Elrod-Adams model

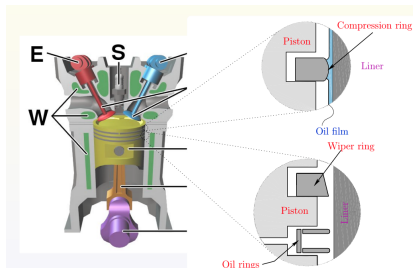
We consider the p - θ model

$$\nabla \cdot \left(\frac{h^3}{12\mu} \nabla p \right) = \frac{S}{2} \frac{\partial h\theta}{\partial x_1} + \frac{\partial h\theta}{\partial t} \text{ in } \Omega$$

is solved under the complementarity conditions

$$\begin{cases} p > 0 & \Rightarrow & \theta = 1 \text{ in } \Omega_+ \\ \theta < 1 & \Rightarrow & p = 0 \text{ in } \Omega_0 \end{cases}$$

with suitable initial and boundary conditions.

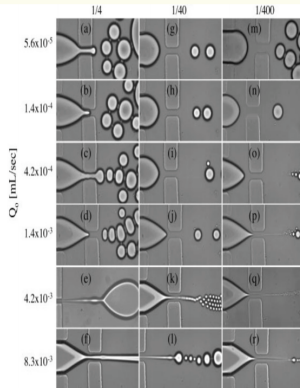


Capillarity effects

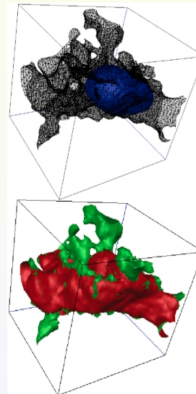


Wetting phenomena

Micro-controlled flows



Two-phase flow in porous media



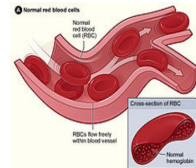
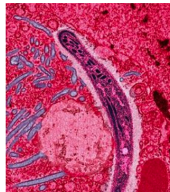
$$\left\{ \begin{array}{ll} -\nabla \cdot (2\mu \mathbf{D}(\mathbf{u})) + \nabla p = \mathbf{f} & \text{in } \Omega \setminus \Gamma(t) \\ \nabla \cdot \mathbf{u} = 0 & \text{in } \Omega \\ \mathbf{u} = \mathbf{g} & \text{on } \Gamma_D \\ [[\boldsymbol{\sigma}]] \cdot \mathbf{\check{n}} = \mathbf{f}_\Gamma & \text{on } \Gamma(t), \end{array} \right.$$

The mechanical behavior of biological membranes is of interest due to its connection to several **human diseases**

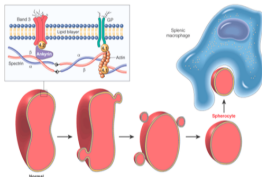
→ Typical examples are:

- Sickle cell anaemia (SCA)
- Spherocytosis
- Malaria

Malaria



Sickle disease

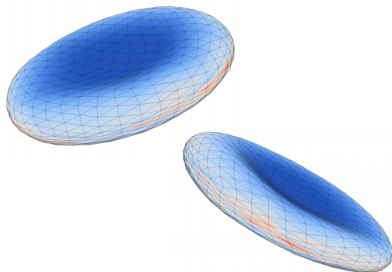


Spherocytosis



$$\int_{\Gamma} 2\mu_s D_{\Gamma} \mathbf{u} : D_{\Gamma} \mathbf{v} - \int_{\Gamma} \pi_s \nabla_{\Gamma} \cdot \mathbf{v} = -d\mathcal{E}(\mathbf{v}) + \int_{\Gamma} \mathbf{f} \cdot \mathbf{v}$$
$$\int_{\Gamma} \xi \nabla_{\Gamma} \cdot \mathbf{u} = 0$$

for all $(\mathbf{v}, \xi) \in \mathbf{V} \times Q$."



- **Matemática e cálculo numérico:**
EDP's, Algebra linear, Métodos numéricos, Analise funcional, etc.
- **Física-Modelagem:**
Leis de conservação de massa, momento, energia, comportamentos constitutivos dos materiais, termodinâmica, etc.
- **Programação:**
Linguagens de alto e baixo nível: C, C++, Fortran, Python, Matlab, **HPC**, etc.

- Métodos do cálculo Numérico;
- Geração de Malhas e Geometria computacional;
- Resolução numérica de EDP's;
- Algebra linear Computacional;
- Introdução à Mecânica dos fluidos computacioanal;
- Introdução ao Método dos elementos finitos;

Projetos de pesquisa

Advanced Configurations for Noise Reduction.

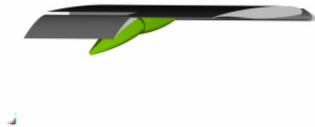
- Funding: Embraer S.A.
- ~ R\$ 3.7 million (2016 – 2018)
- PI: Fernando M. Catalano, EESC/USP
- Associates:
 - Leandro Franco de Souza, ICMC/USP
 - Paulo Celso Greco Junior, EESC/USP
- 2 PhD students, 5 MsC student



Numerical example



o)



p)



q)



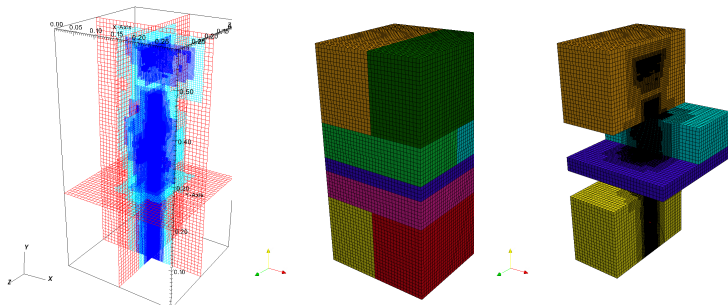
r)

Mathematical and Numerical Developments in Multiphase Flows Applied to Refining Processes.

- Funding: Petrobras S.A.
- ~ R\$ 1 million (2013 – 2015, 2017 – 2018)
- PI: Antonio Castelo Filho, ICMC/USP
- Associates:
 - Adenilso da Silva Simão, ICMC/USP
 - Leandro Franco de Souza, ICMC/USP
 - Fabricio Simeoni de Sousa, ICMC/USP
- Collaborators:
 - Jonas Laerte Ansoni, ICMC/USP
- 1 postdoc, 2 PhD students, 2 MsC student

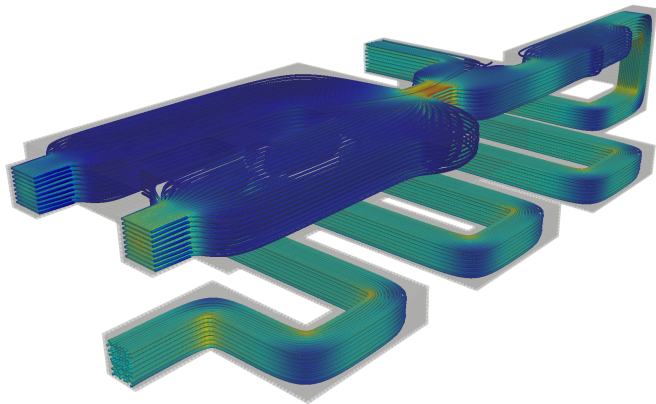


Some results



Mesh and domain decomposition.

Some results



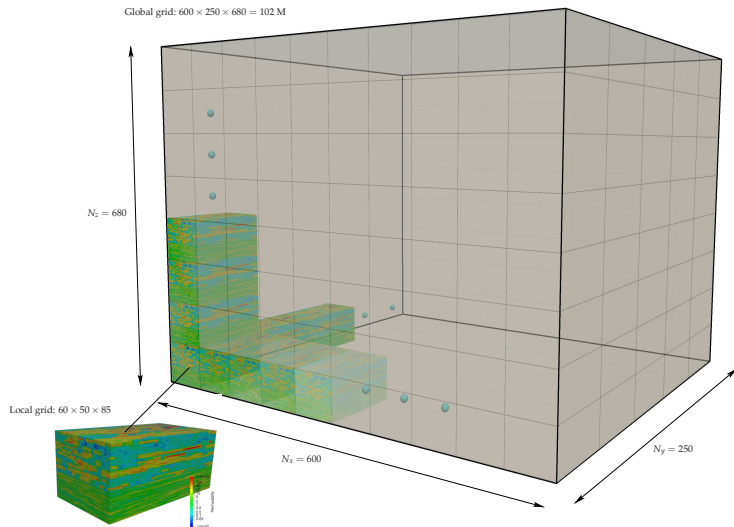
Geometry and streamlines for the complex 3D array of micro channels.

Multiscale methods for the simulation of petroleum reservoirs

- Funding: Petrobras S.A.
- ~ U\$ 1 million (2017 – 2020)
- PI: Fabricio Simeoni de Sousa, ICMC/USP
- Associates:
 - Gustavo C. Buscaglia, ICMC/USP
 - Roberto F. Ausas, ICMC/USP
- Collaborators:
 - Felipe Pereira, Univ. of Texas at Dallas, USA
 - Eduardo Abreu, Unicamp
- 2 postdocs, 4 PhD students



A more realistic case



Nos próximos anos a tendência é combinar estes métodos com outras ferramentas para tentar extrair mais informação e entender melhor o comportamento destes sistemas:

- Machine learning, Deep learning
- Inteligência Artificial (IA)
- Algoritmos de otimização e controle ótimo
- Análise de quantificação de incertezas
- Big Data
- etc.