FLUID DIODES DESIGN BY USING TOPOLOGY OPTIMIZATION METHOD

Bruno Caldas de Souza

Prof. Dr. Emílio Carlos Nelli Silva
Dept. Mechatronics Engineering
University of São Paulo, Brazil

Research Centre for Gas Innovation

cleaner energy for a sustainable future

RCGI intern Workshop

August 20th, 2018

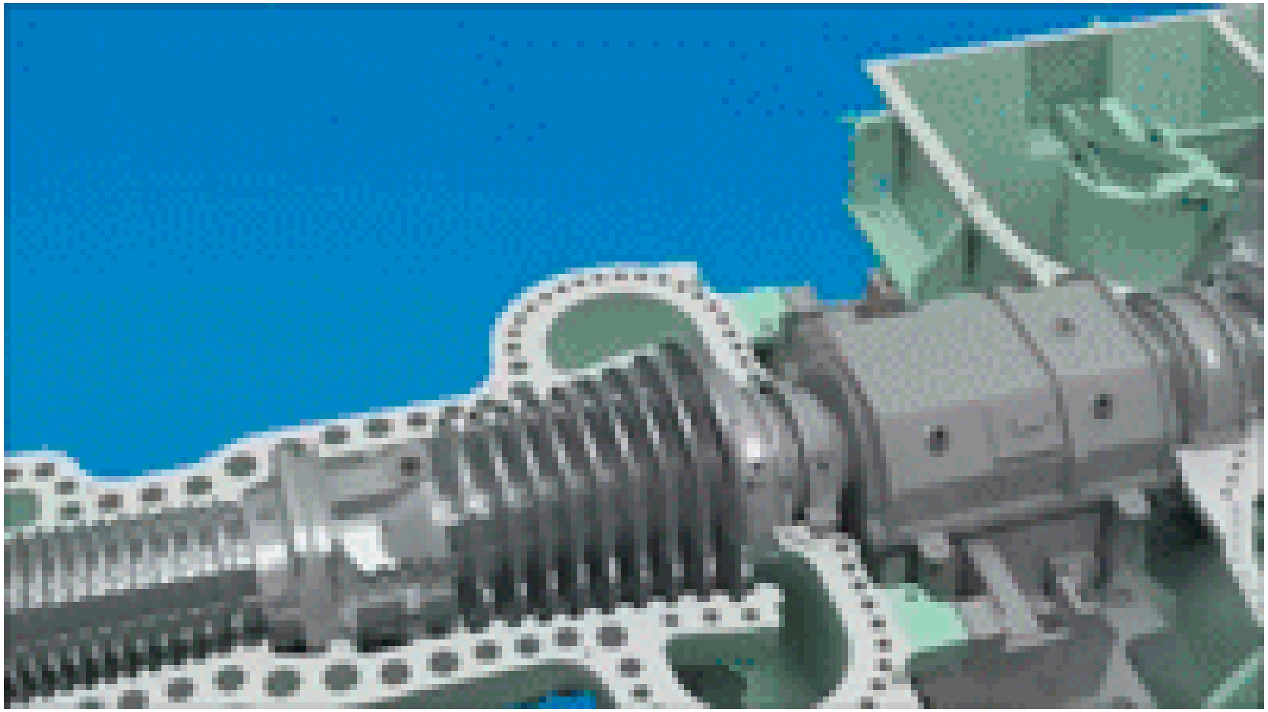
Outline

- Introduction to Fluid Diodes
- Motivation of the Project
- Objective
- Problem Formulation
- Topology Optimization Method
- Results
- Conclusions

Introduction – Fluid Diodes

- A fluid diode is a device without moving parts which causes smaller flow resistance in one direction compared to the opposite.
- The basic concept is shown on the right and it was patented by Nikola Tesla in 1916.
- A special kind of fluid diodes applied to turbines is the labyrinth seal.

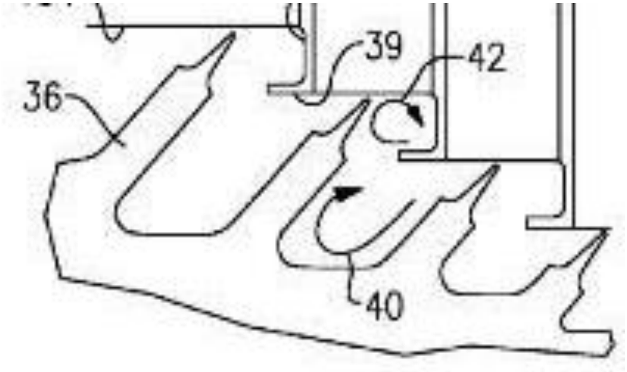
Labyrinth Seal Application Example



Turbo parts steam turbine advanced sealing system (Link: https://www.youtube.com/watch?v=942gtbwBmcw)

Introduction – Motivation

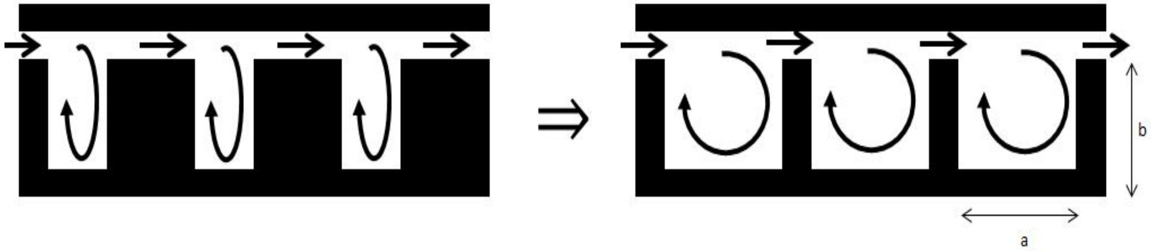
- Labyrinth Seals are used extensively in machines with high pressure and temperature, like turbines and pumps [1], even with their inherent leakage.
- 60% of methane emissions are caused by leaks in pumps, turbines or pneumatic devices, coming to leak about 4m³ a day, which amount to about 3,965 m³ per year for each device [2].
- Supercritical Carbon Dioxide (S-CO2) is a promising working fluid for future high efficiency power cycles, but the leakage from compressors may be considered. [3]
- The factors influencing this fluid loss include the design and their maintenance. The first is the most effective in combating gas emissions.
- The shape of these kind of devices are so relevant that there are patents [4] exploring design.



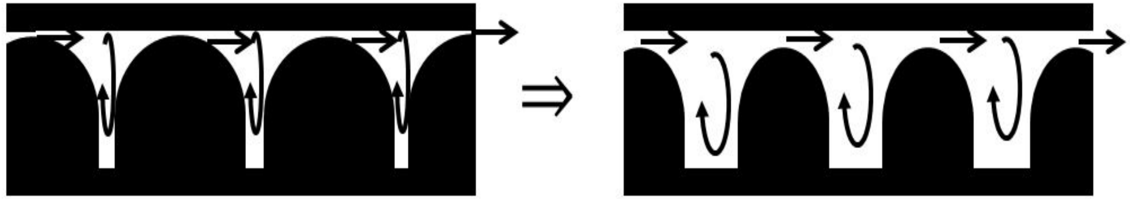
[1] M.P. Boyce. Gas Turbine Engineering Handbook, 4. ed., Elsevier, 2012
[2] EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 – 2009. Abril, 2011
[3]Yuan, Haomin, et al. "Experiment and numerical study of supercritical carbon dioxide flow through labyrinth seals." The 4th International Symposium-Supercritical CO2 Power. 2014.
[4] UNITED TECHNOLOGIES CORPORATION; Charlos C.W et al; Gas Turbine Engine with canted pocket and canted knife edge seal;2012.

Topology Optimization of Labyrinth Seals

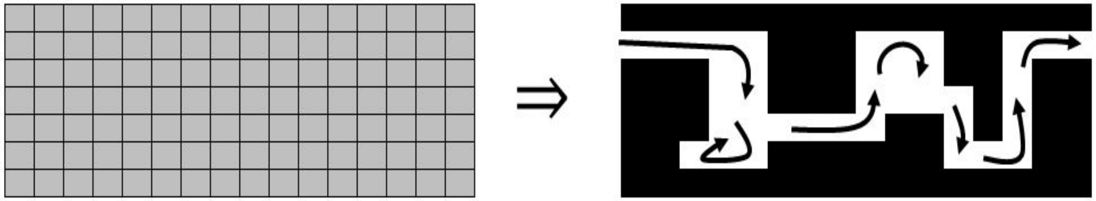
Parametric Optimization



Shape Optimization



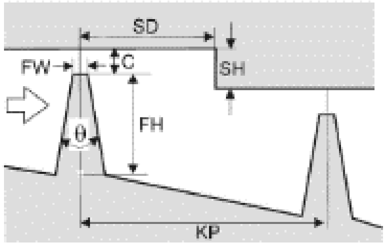
Topology Optimization

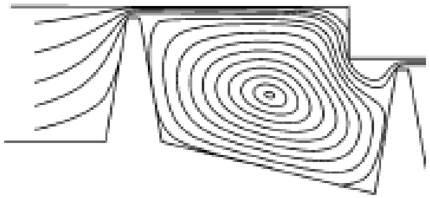


Relevance of Labyrinth Seals Geometry

V. Schramm[1]

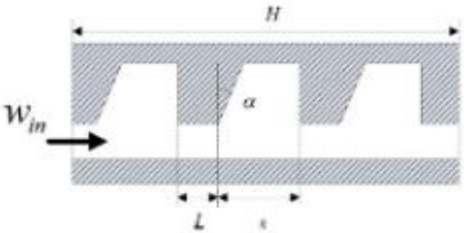
Optimization of sealing parameters such as length and width in order to minimize flow

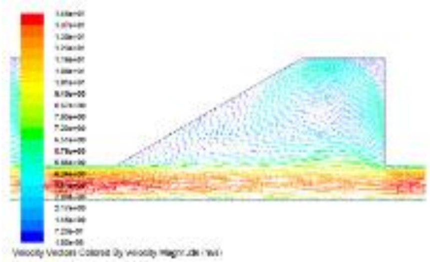




S.J. Yoon[2]

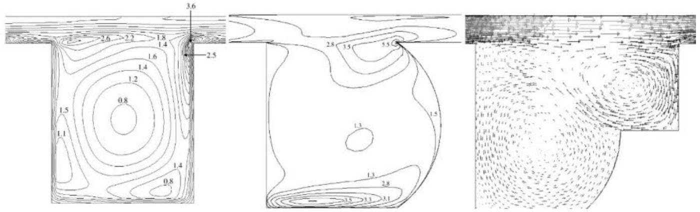
Optimization of parameters with experimental and statistical data in order to maximize the pressure loss





S.P. Asok[3]

Neural Networks combined with CFD analysis to optimize parameters of one square and another curve joint

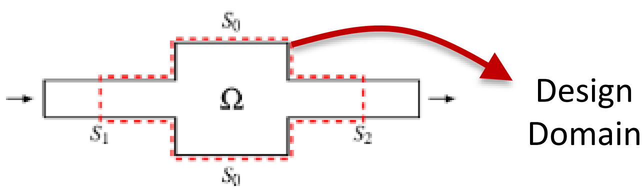


[1] V. Schramm et al.; Shape Optimization of a Labyrinth Seal Applying the Simulated Annealing Method 2004.
[2] S.J. Yoon et al.; Numerical and experimental investigation on labyrinth seal mechanism for bypass flow reduction in prismatic VHTR core, 2013
[3] S.P.Asok et al.; Neural network and CFD-based optimisation of square cavity and curved static labyrinth seals 2007

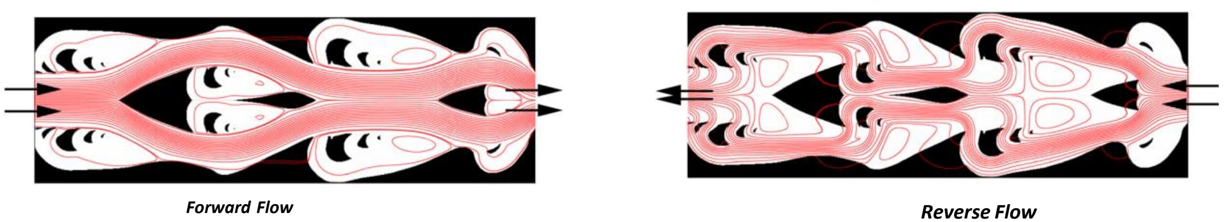
Topology Optimization applied to Tesla Valves

- Another approach is similar what Lin, Sen(2015) [1] performed in Tesla Valves, minimizing "diodicity", or in other words, maximizing the viscous dissipation

Traditional Tesla Valve



Tesla Valve after Topology Optimization



[1] Sen Lin, et al. ; Topology Optimization of Fixed-Geometry Fluid Diodes; Journal of Mechanical Design, 2015

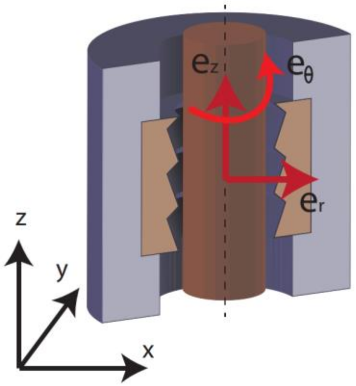
Objective

- Study of the design of labyrinth seal using topology optimization method for turbines and compressors.
- Implementation of a Topology Optimization Method of labyrinth seals considering the rotation of the moving parts (2D-Swirl).

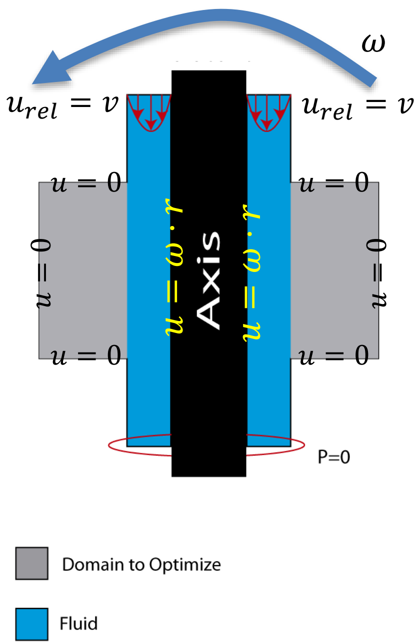
Hypothesis

- Incompressibility
- Time-Independency

Problem Formulation – NS Equation – 2DSwirl



For the design of fluid diodes with rotational axis, the 2D Swirl modeling with relative velocities may be necessary



$$
\begin{cases}
\nabla \cdot \mathbf{u} = 0 \\
\rho \dfrac{D\mathbf{u}}{Dt} = -\nabla \mathrm{p} + \mu \nabla^2 \mathbf{u} + \underbrace{\rho \boldsymbol{f}}_{\text{Inertial forces}} + \alpha \mathbf{u}
\end{cases}
$$

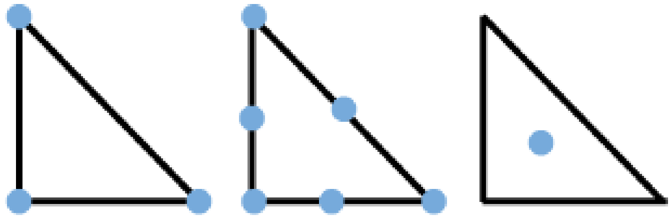
$$\rho \cdot f_{centrif} = -\rho \boldsymbol{\omega} \wedge (\boldsymbol{\omega} \wedge \boldsymbol{r})$$

$$\rho \cdot f_{coriolis} = -2\rho \boldsymbol{\omega} \wedge \boldsymbol{u_{rel}}$$

$$\rho \frac{D\boldsymbol{u_{rel}}}{Dt} = -\nabla \mathrm{p} + \mu \nabla^2 \boldsymbol{u_{rel}} - \rho \boldsymbol{\omega} \wedge (\boldsymbol{\omega} \wedge \boldsymbol{r}) - 2\rho \boldsymbol{\omega} \wedge \boldsymbol{u_{rel}} + \alpha \mathbf{u}$$

Finite Element Method

- This work uses the Taylor-Hood element for the finite element analysis, because it has been shown one fast and easy element to converge.



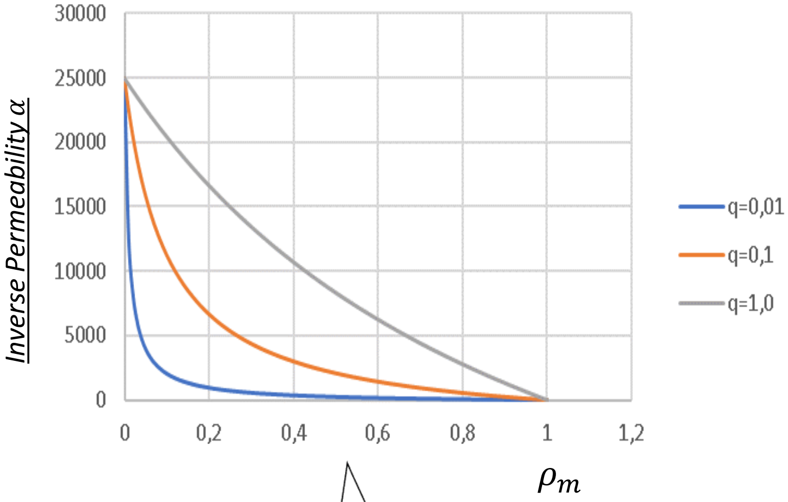
Problem Formulation – Material Model

- The material model [1] is implemented into the Navier-Stokes Equation:

$$\rho \frac{D\boldsymbol{u_{rel}}}{Dt} = -\nabla \mathrm{p} + \mu \nabla^2 \boldsymbol{u_{rel}}$$

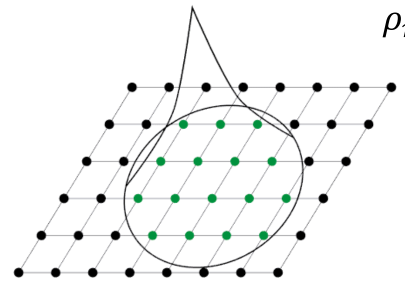
$$-\rho\boldsymbol{\omega} \wedge (\boldsymbol{\omega} \wedge \boldsymbol{r}) - 2\rho\boldsymbol{\omega} \wedge \boldsymbol{u_{rel}} + \alpha\mathbf{u}$$

$$\alpha(x) = \alpha_{min} + (\alpha_{min} - \alpha_{max})\rho_m \cdot \frac{1+q}{\rho_m + q}$$



- Filtering in topology optimization based on Modified Helmholtz Equation[2]:

$$\tilde{\rho}(x) = (F * \rho)(x) = \int_{\Omega F} F(x-y)\rho(y)dy \quad and \ -r^2\nabla^2\tilde{\rho} + \tilde{\rho} = \rho$$



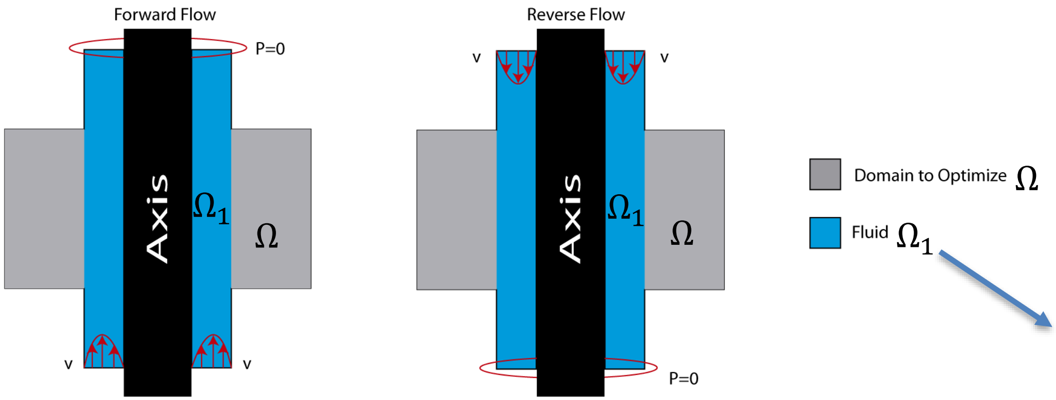
[1] Borrvall, Thomas, and Joakim Petersson. "Topology optimization of fluids in Stokes flow." *International journal for numerical methods in fluids*41.1 (2003): 77-107.
[2] Lazarov, Boyan Stefanov, and Ole Sigmund. "Filters in topology optimization based on Helmholtz-type differential equations." International Journal for Numerical Methods in Engineering 86.6 (2011): 765-781.

Topology Optimization Formulation

- Diodicity of Energy Dissipation:

$$
\min \quad \frac{1}{\mathrm{Di}'} + \int_\Omega \rho \cdot (1-\rho)dx = \frac{\Phi(\mathbf{u_f}, p_f)}{\Phi(\boldsymbol{u_r}, p_r)} + \int_\Omega \rho \cdot (1-\rho)dx = \frac{\int_\Omega \frac{1}{2}\mu(\nabla \boldsymbol{u_f} + \nabla \boldsymbol{u_f}^T) + \alpha \boldsymbol{u_f}^2 \, dx}{\int_\Omega \frac{1}{2}\mu(\nabla \boldsymbol{u_r} + \nabla \boldsymbol{u_r}^T) + \alpha \boldsymbol{u_r}^2 \, dx} + \int_\Omega \rho \cdot (1-\rho)dx
$$

$$
s.t: \quad \alpha_{min} \le \alpha \le 1, \quad V_{min} \le V \le V_{max}
$$

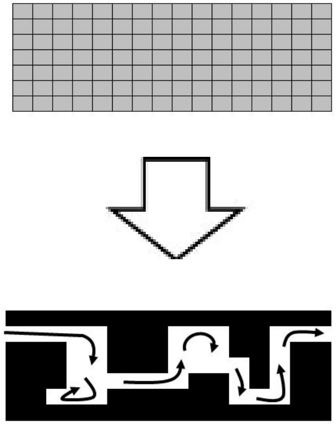


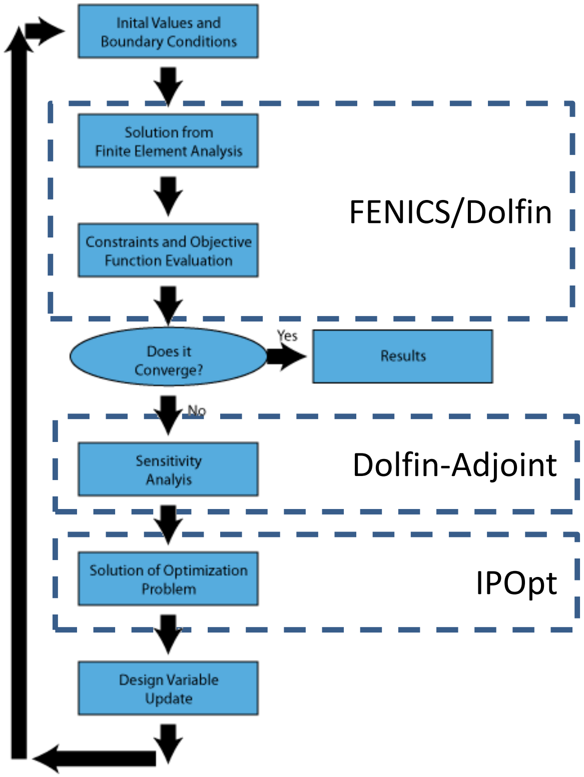
Φ_f: *Energy Loss in the forward flow*
Φ_r: *Energy Loss in the reverse flow*

Diodicity is the concept of the difference in loss energy mechanisms in the two flow directions

Local Volume Constraint: $V_{fluid} = 100\%$

Methodology





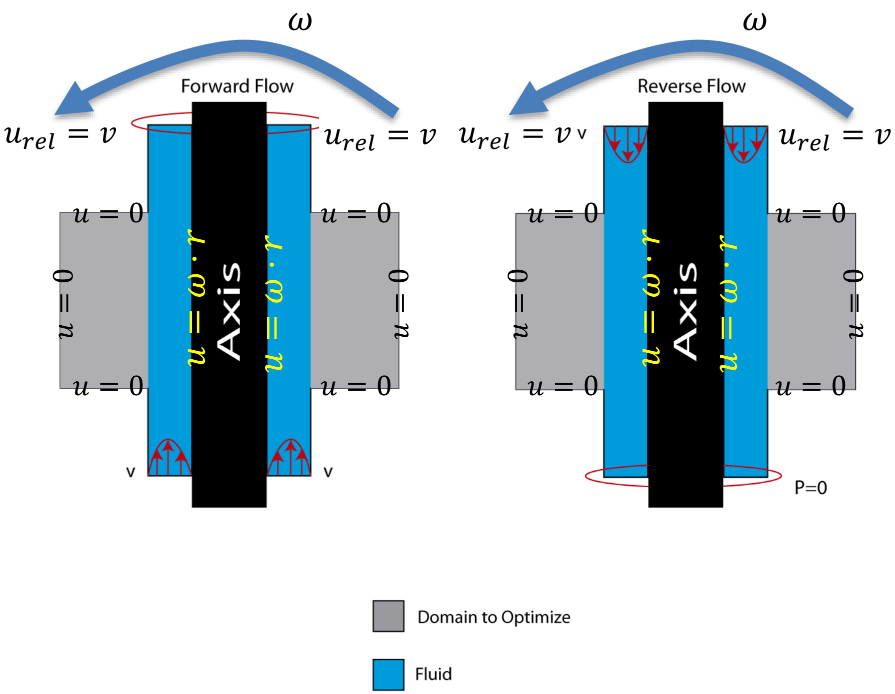
fenics project

dolfin-adjoint

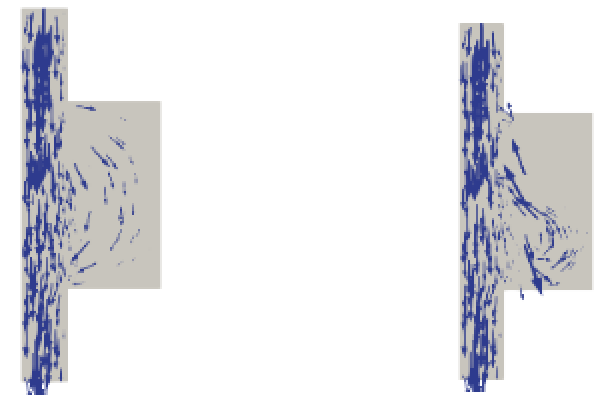
Ipopt
*(**I**nterior **P**oint **OPT**imizer*
)

**all used codes are open software according to GNU*

Results – Flow direction



Low Velocities　　High Velocities

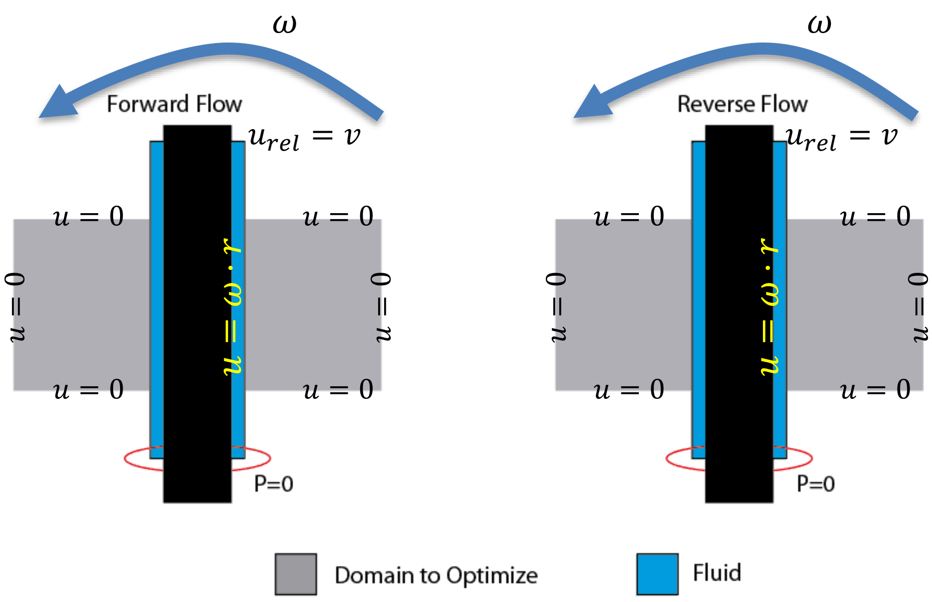


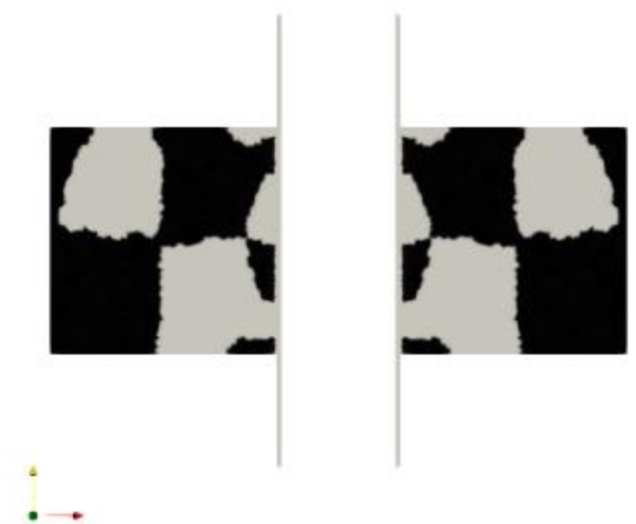
$Re = 100$　$Re = 300$　$Re = 600$　$Re = 1000$

Results – Helmholtz-type equations

Specifications:
2,5D plane
$Re = 50$
$Da = 3{,}3 \cdot 10^{-5}$
$\omega = 100 rad/s$

r=0

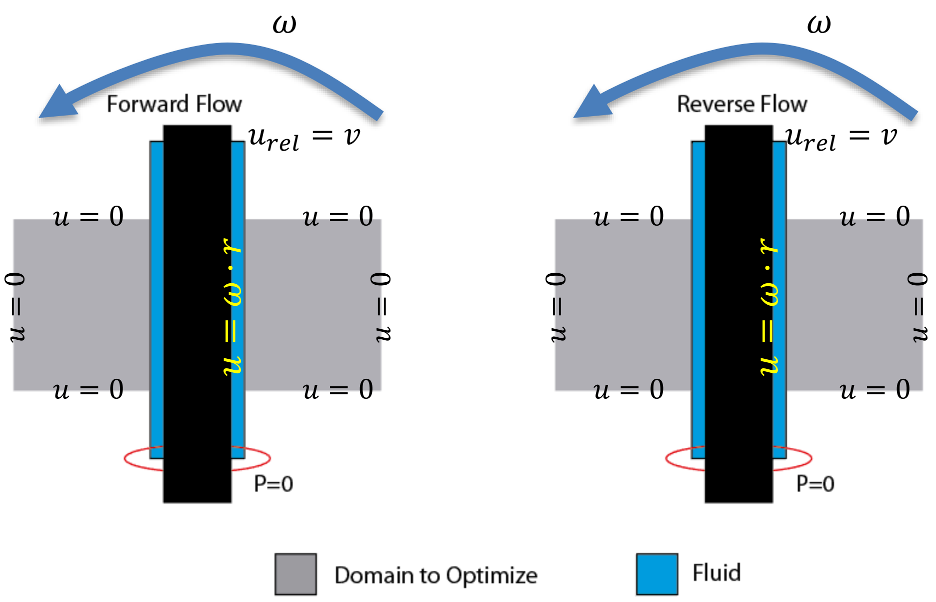


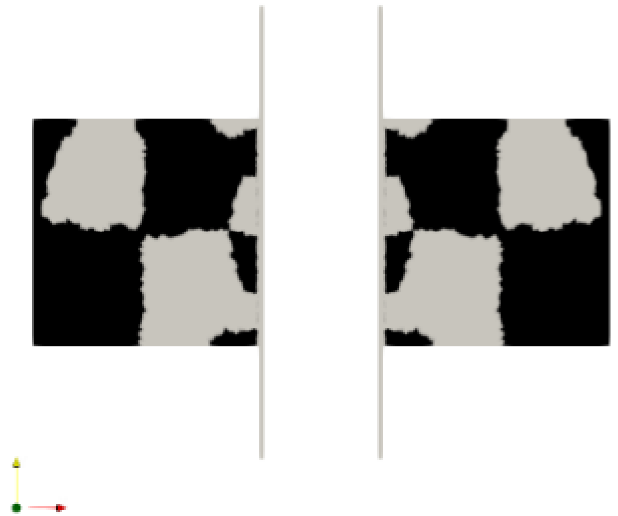


Results – Helmholtz-type equations

Specifications:
2,5D plane
$Re = 50$
$Da = 3{,}3 \cdot 10^{-5}$
$\omega = 100 rad/s$

r=0.1

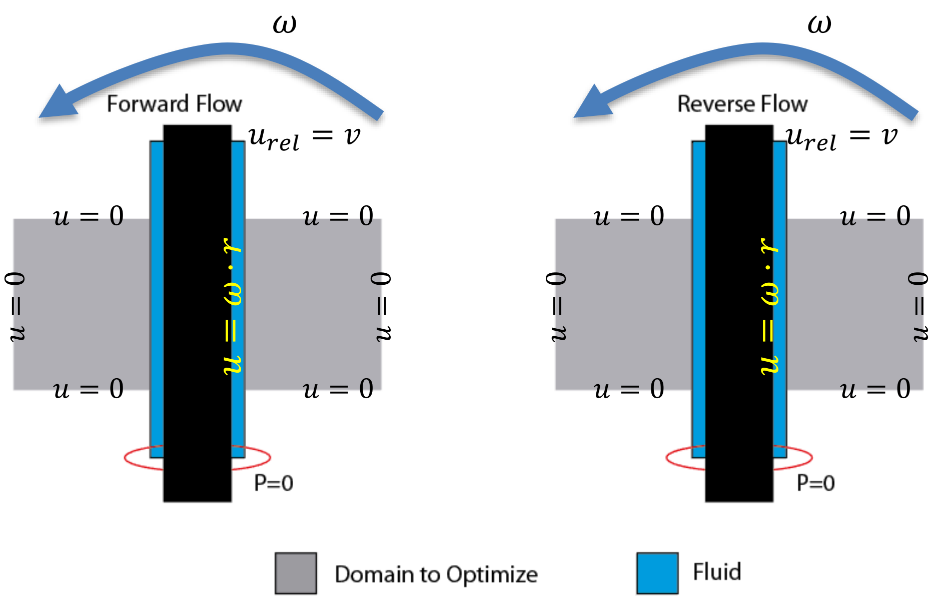




Results – Helmholtz-type equations

Specifications:
2,5D plane
$Re = 50$
$Da = 3{,}3 \cdot 10^{-5}$
$\omega = 100 rad/s$

r=0.4



Results – Helmholtz-type equations

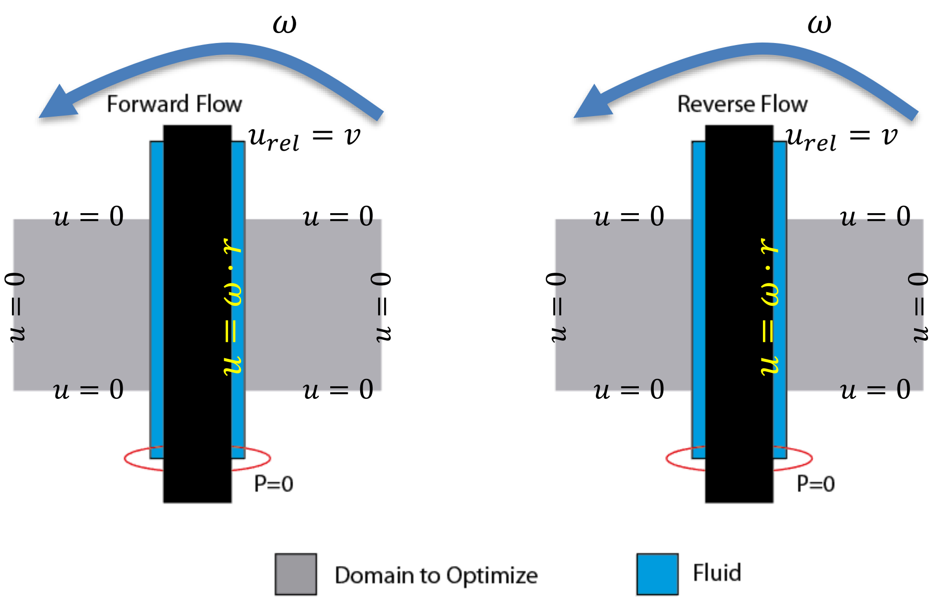
Specifications:
2,5D plane

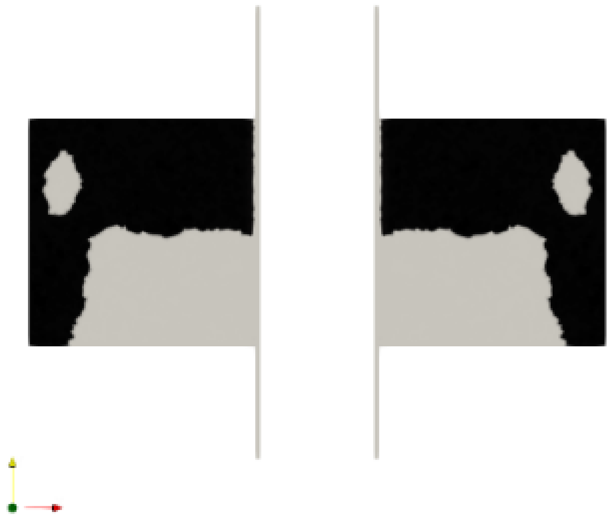
$Re = 50$

$Da = 3{,}3 \cdot 10^{-5}$

$\omega = 100 rad/s$

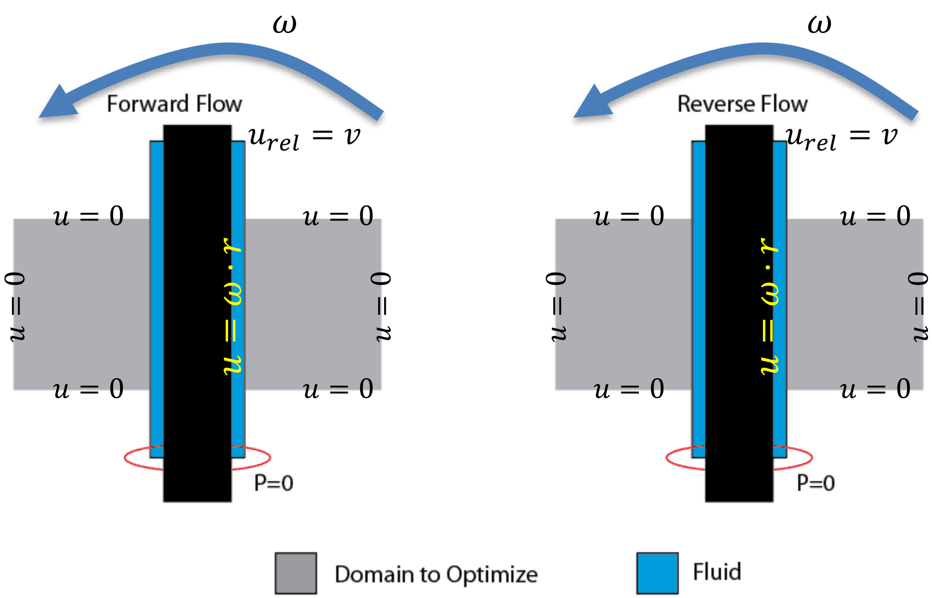
r=0.8

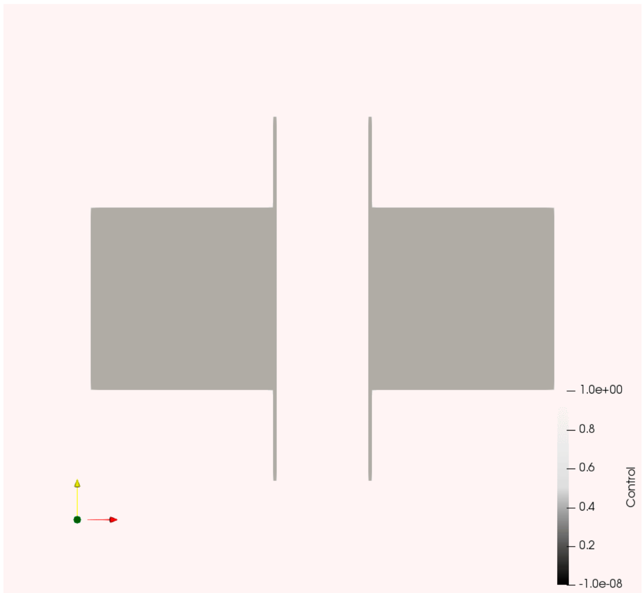




General Results

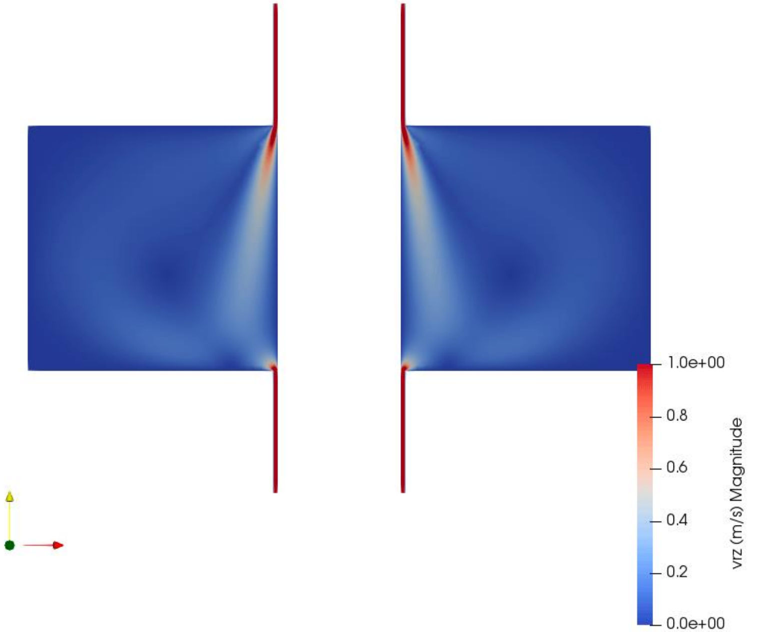
$$\omega = 10 rad/s$$
$$Re = 400$$
$$Da = 3{,}3 \cdot 10^{-5}$$



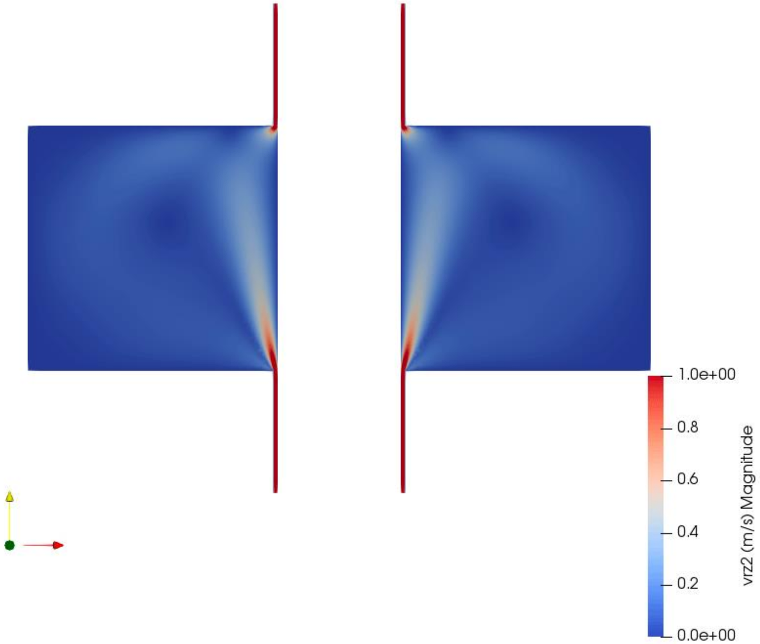


General Results – Velocity Plot during Optimization

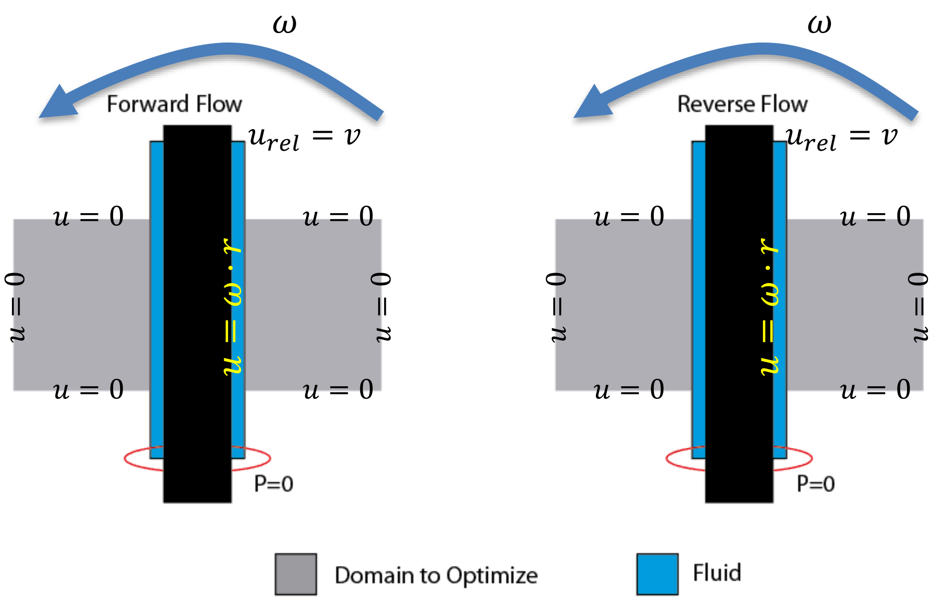
Forward Case



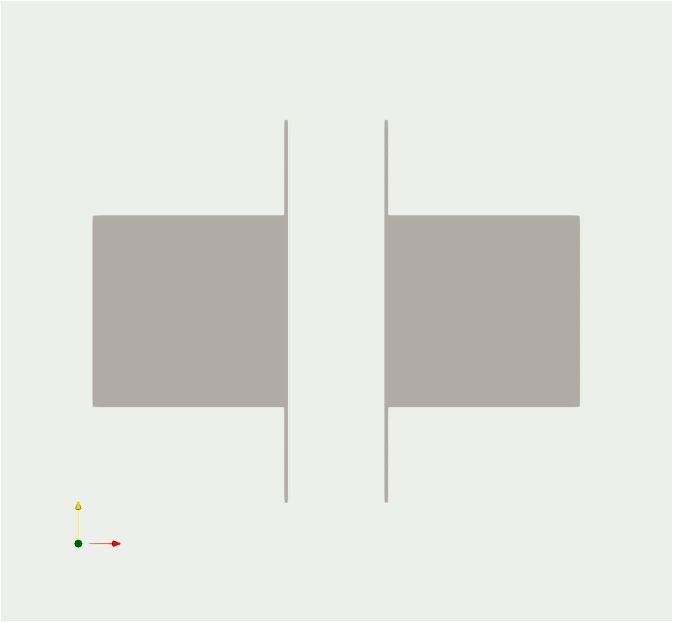
Reverse Case



General Results

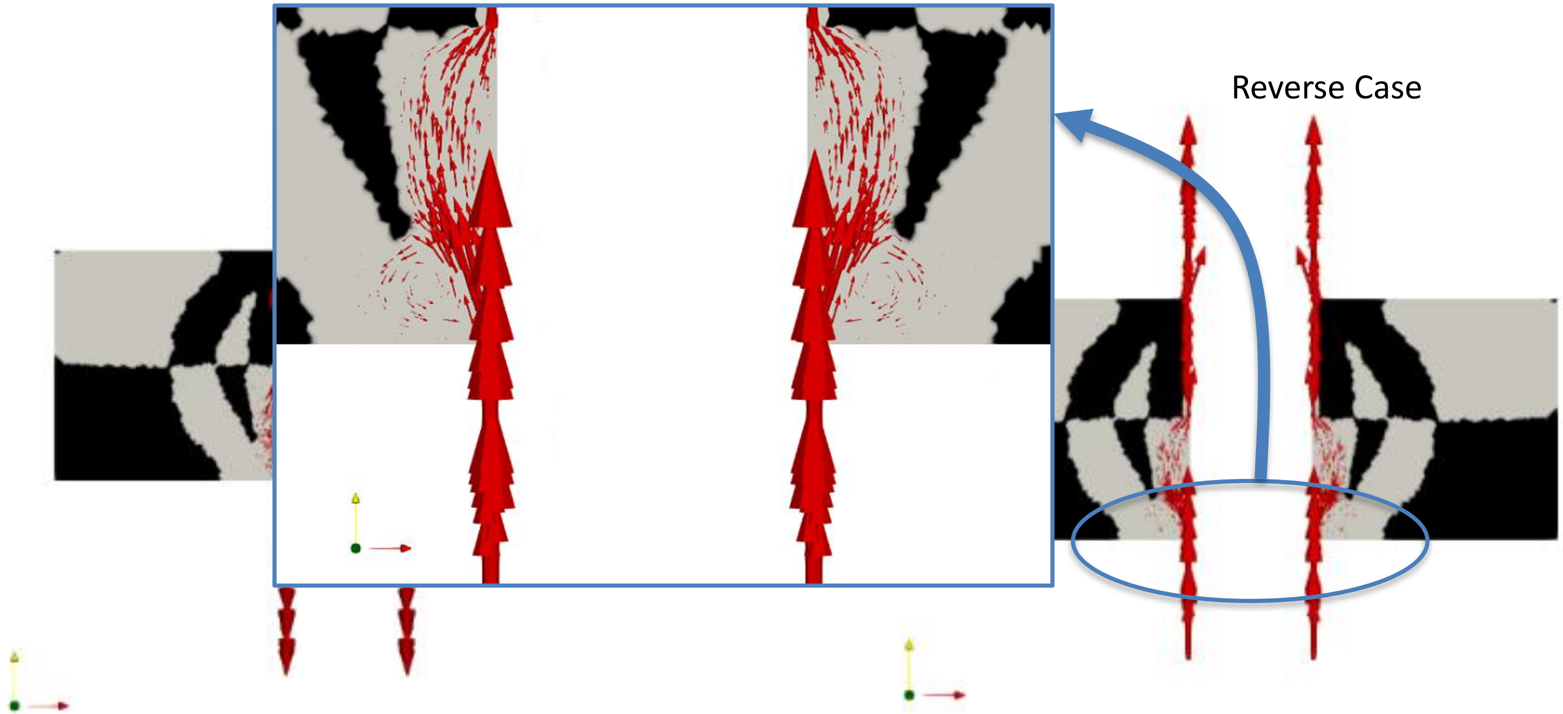


$$\omega = 100 rad/s$$
$$Re = 300$$
$$Da = 3{,}3 \cdot 10^{-5}$$



General Results – Fluid Flow

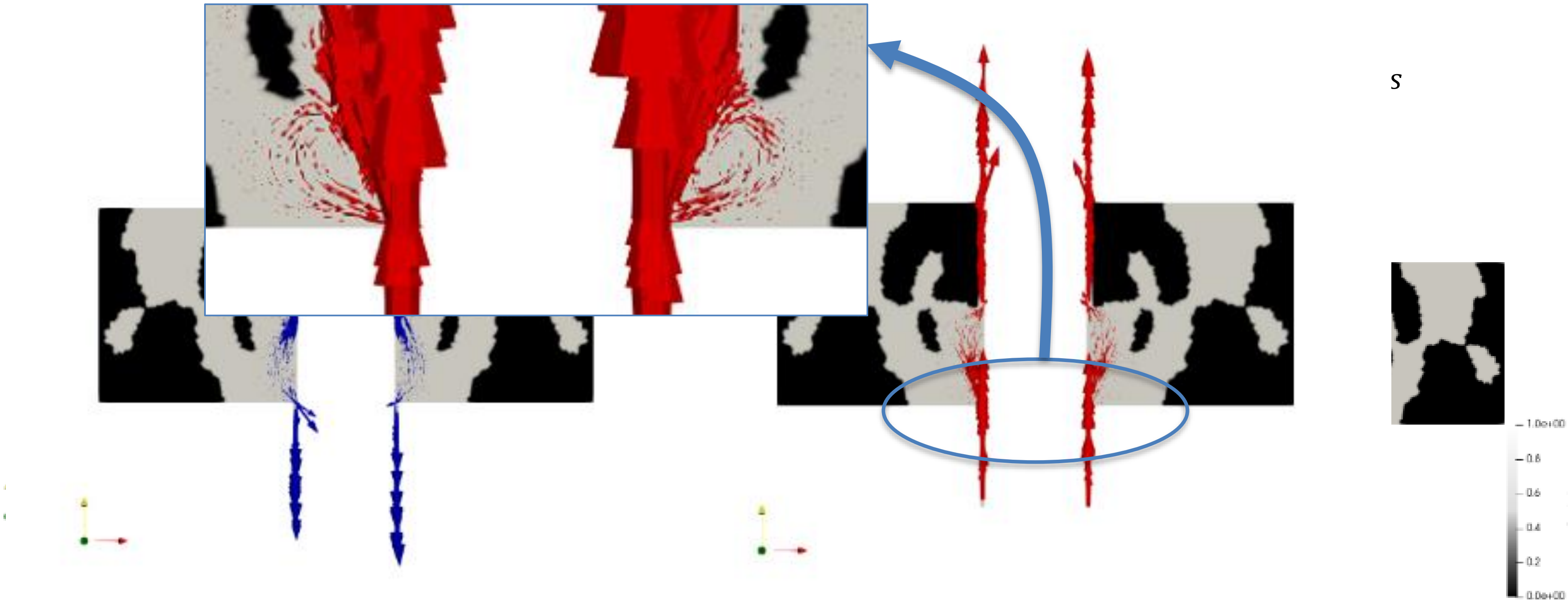
Specifications:
2D plane
$Re = 100$
$Da = 3{,}3 \cdot 10^{-5}$



Results – Influence of Angular Velocity

Specifications:
2,5D plane
$Re = 300$
$Da = 3{,}3 \cdot 10^{-5}$

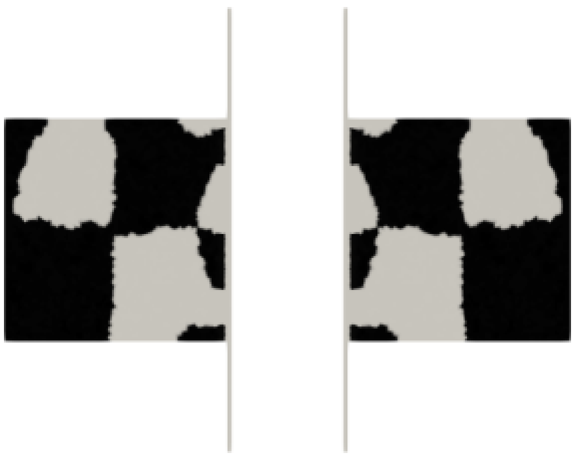
s



[1] Subramanian, S., Sekhar, A.S. and Prasad, B.V.S.S.S., 2015. Influence of combined radial location and growth on the leakage performance of a rotating labyrinth gas turbine seal. Journal of Mechanical Science and Technology, 29(6), pp.2535-2545.

Results – Aspect Ratio

Specifications:
2,5D plane
$Re = 50$
$Da = 3{,}3 \cdot 10^{-5}$
$\omega = 100 rad/s$



Aspect 1:1

Aspect 1:1

Aspect 1:3

Conclusions

- Labyrinth Seals design can be improved considering rotation.
- Small values for rotation may influence the final topologies.
- There are several geometry parameters that may influence the flow circulation.
- Helmholtz-type equations can be used as results' filter and may be used with caution.
- The aspect ratio of the design domain is of medium importance to the final geometry.

Future Work:

- Turbulence Models
- Hydraulic Application
- Efficiency of the simulation
- Prototyping

Research Centre for Gas Innovation

cleaner energy for a sustainable future

THANK YOU

facebook.com/GasInnovation

twitter.com/rcgipage

www.usp.br/rcgi