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Design for Additive Manufacturing: TOffee

F Montomoli, A Gaymann, M Pietropaoli

Imperial College of London
UQLab
UK

Smith institute
for industrial mathematics and system engineering

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UQLab

People: 5 Post Docs, 5 PhD students, 1 Academic

Sponsors-Collaborations: Rolls-Royce (UK), General Electric (UK-Italy), Criepi (Japan), Airbus (UK-Fr-DE), EPSRC, NASA Langley (US), etc

Major Areas: Uncertainty Quantification and Additive Manufacturing

Prizes of the Lab: Lloyd's Prize runner up for Science of Risk, John Frances Prize (best Imperial PhD student), Elaine Austin Centenary Memorial Prize, UK Parliament invitation (STEM for Britain), Reynolds prize poster finalist etc

Spinouts: MonolithAI MONOLITH **TOffee** *TOffee*

imagination at work ROLLS ROYCE Rolls-Royce® AIRBUS AN EADS COMPANY CRIEPI Central Research Institute of Electric Power Industry

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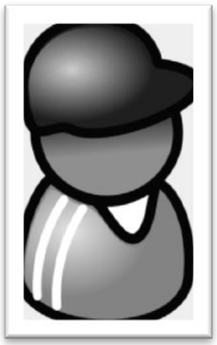
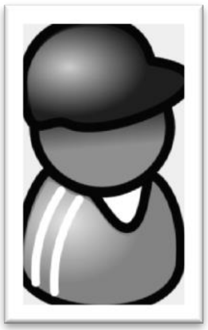


Dr V Badalassi



N Pepper

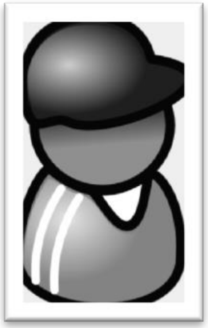
A Cassinelli

A Gaymann

N Casari

H Gauch

Dr M. Pietropaoli



Dr Hui Xu

Dr G Castiglioni

Dr R. Ahlfeld

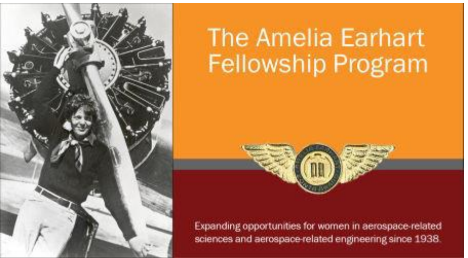
Prof F Montomoli

Arianna

Recent Prizes

- **Audrey**: Amelia Earhart Fellowship, worldwide prize, one of the best 32 females worldwide in aviation
- **Marco**: EPSRC Doctoral Prize, STEM for Britain selected at UK Parliament as one of best UK researches, Take AIM second place, CDT Prize
- **Richard**: EPSRC Fellowship, RAEng fellowship, Francis Prize as best PhD student of Imperial College
- **MonolithAI** named one of the best 7 Deep Science Startups in the World for industry 4.0
- **TOffee**: Amazon AWS programmable 2018 winner

Programm/able



STEM for BRITAIN

EPSRC
Engineering and Physical Sciences
Research Council

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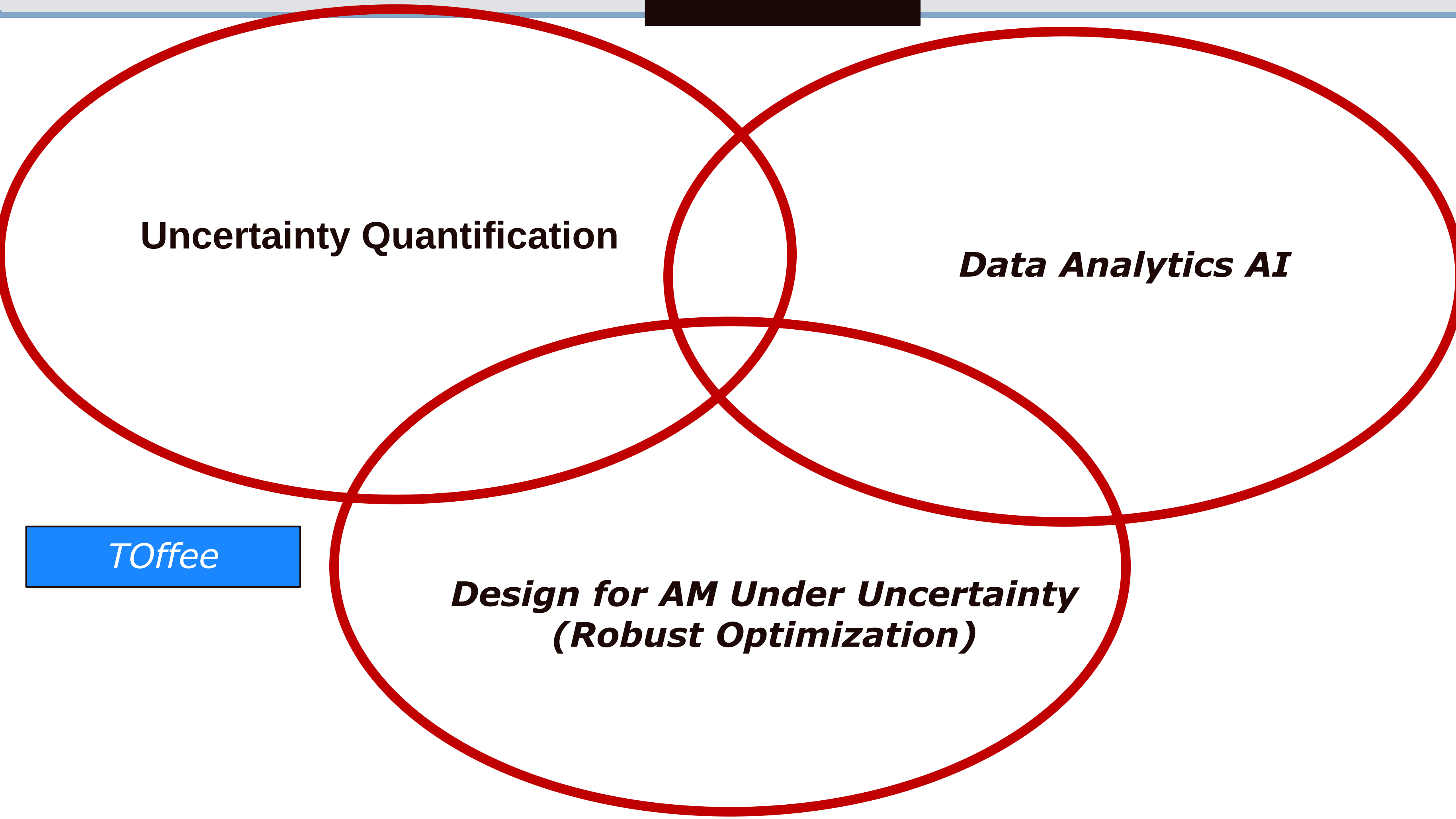
Research Areas

MONOLITH



TOffee

TOffee optimizes Under Uncertainty

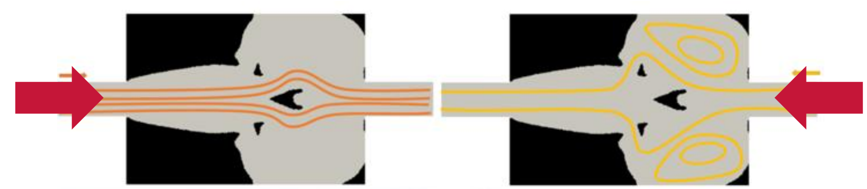
- Toffee is an in house optimization code, fluid-structure:

- Conjugate Heat Transfer and Heat Exchangers
- Bi-directional flows (valves without moving parts)
- Low pressure losses
- Robustness against variations
- Applied to real cases
- ….. And much more

Valve Without moving parts

low losses

High losses

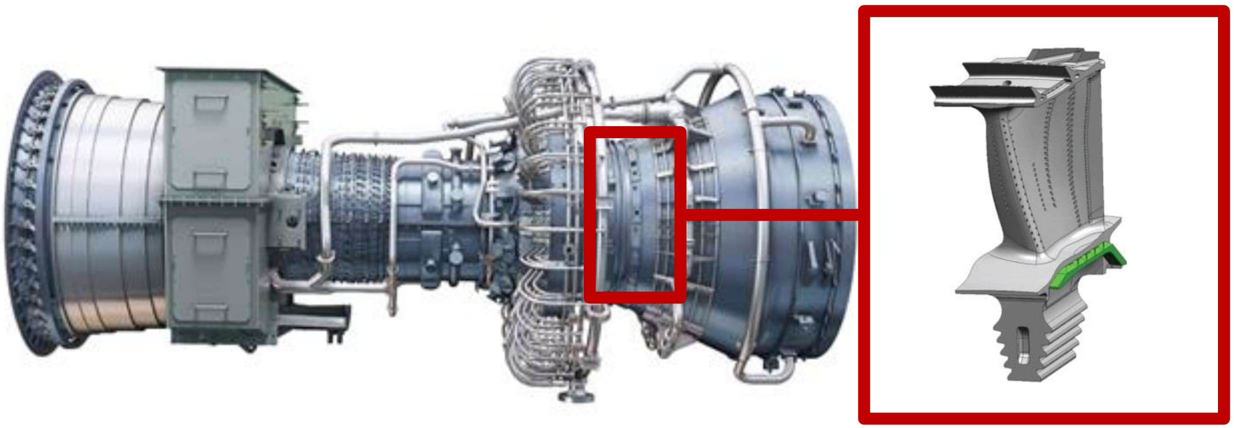


Gas Turbine Cooling: our vision

Increase of efficiency and reliability of gas turbines

- *Higher TET ~2200K in the last generation engines*
- *Variation of ~30K can reduce by half the life of the engine*

More complex and efficient coolant systems



Bio-Inspired coolant design

The design process must take into account several aspects

- *Pressure drop of the coolant flow*
- *Temperature of the mechanical parts*
- *Temperature gradients across the whole blade*
- *Reliability against mechanical stress*
- ***Manufacturing constraints***

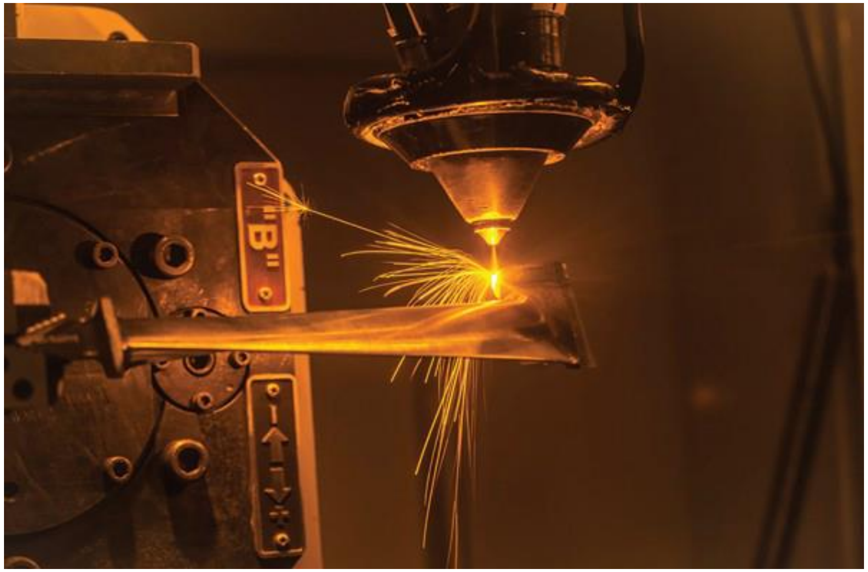
.. . and it must be automatic!!!

How to build it: Additive Manufacturing (AM)

- *Production of complex mechanical parts, avoiding standard manufacturing operation (drilling, milling…)*

- *Today is used in the wrong way: same part design……*

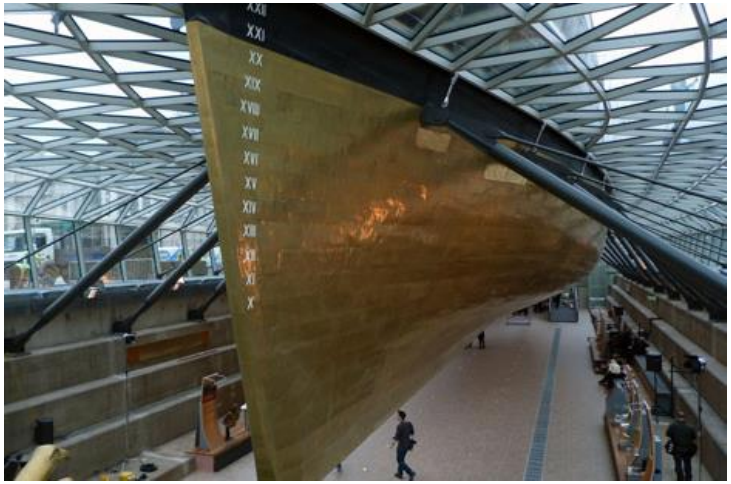
- *It is a common problem when you have a new manufacturing technology*



New Manufacturing… usually same design

Same design, different manufacturing process

Wooden ship



Metal hull, Cutty Sark, London

New Manufacturing… usually same design

Same design, different manufacturing process

Wooden ship

Metal hull, Cutty Sark, London

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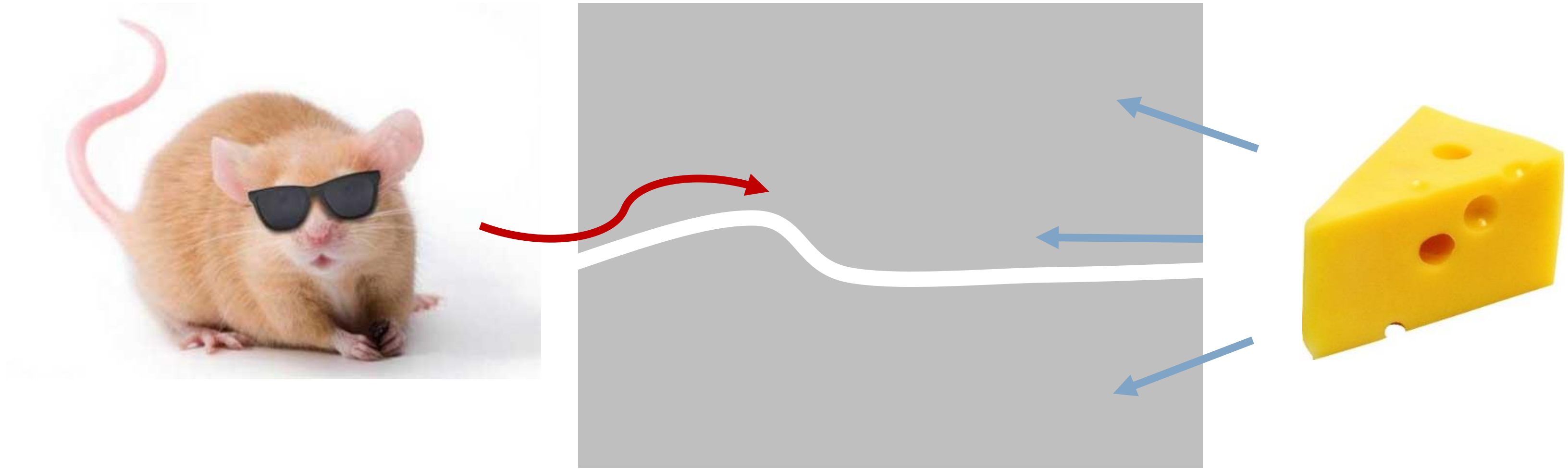
Adjoint Algorithm



p

v

T

Primal Variables

q

u

τ

Adjoint Variables

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Theoretical Model

Lagrangian optimisation approach

$$L = F - \int_{\Omega} \xi_i R_i \, d\Omega$$

F *Objective Function*

R_i *Constraints – Fluid governing equations for incompressible flow*

ξ_i *Lagrangian multipliers – Adjoint variables*

The domain is a porous medium with variable impermeability α

Theoretical Model

Lagrangian optimisation approach

$$L = F - \int_{\Omega} \xi_i R_i \, d\Omega$$

Continuity $\nabla \cdot v = 0$

Momentum $v \cdot \nabla v = -\frac{\nabla p}{\rho} + \nabla \cdot (\nu \nabla v) - \alpha v$

Energy $v \cdot \nabla T = \frac{1}{\rho c} \nabla \cdot (k \nabla T)$

The solution must verify $\delta_{\alpha} L = 0$

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Adjoint Optimisation

After a long computation, the lagrangian variation $\delta_\alpha L$ *is found*

- *A set of adjoint equations and adjoint boundary conditions is derived to evaluate the adjoint variables*

$$\nabla \cdot u = 0$$

$$-v \cdot (\nabla u + \nabla^t u) = -\frac{\nabla q}{\rho} + \nabla \cdot (\nu \nabla u) - \alpha u - c\tau \nabla T$$

$$-v \cdot \nabla \tau = \frac{1}{\rho c} \nabla \cdot (k \nabla \tau)$$

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Objective Functions

Stagnation pressure dissipation and heat transfer must be optimised

$$F = \omega_1 f_1 + \omega_2 f_2$$

Pressure drop to be minimised

$$f_1 = \int_\Sigma \left(p + \frac{1}{2}\rho |v|^2 \right) v_n \; d\Sigma$$

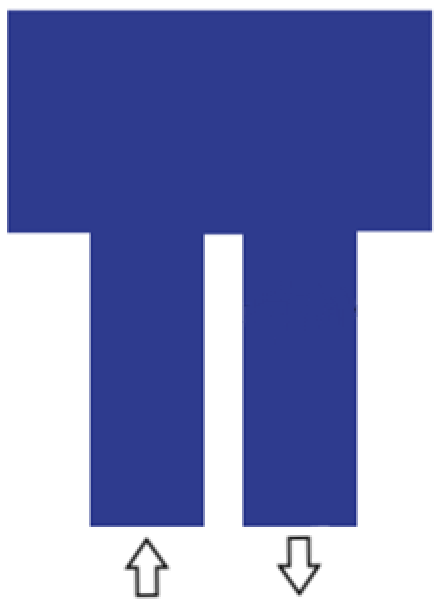
Temperature gain to be maximised

$$f_2 = \int_\Sigma \rho c \, T v_n \; d\Sigma$$

Results - U-Bend case

Test case for pressure drop optimisation

- *Comparison are made with the standard case*



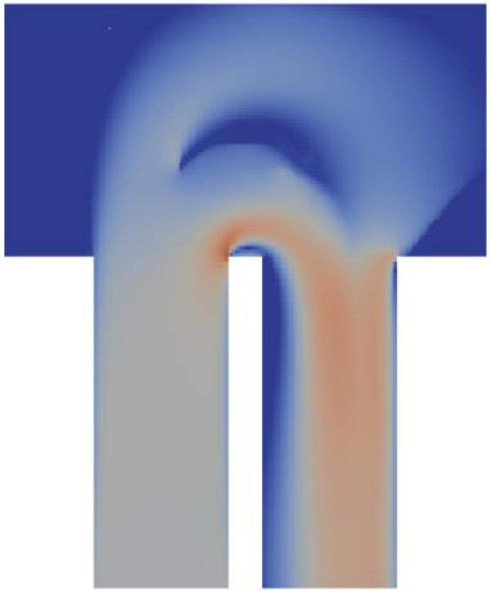
TO Domain

Standard case

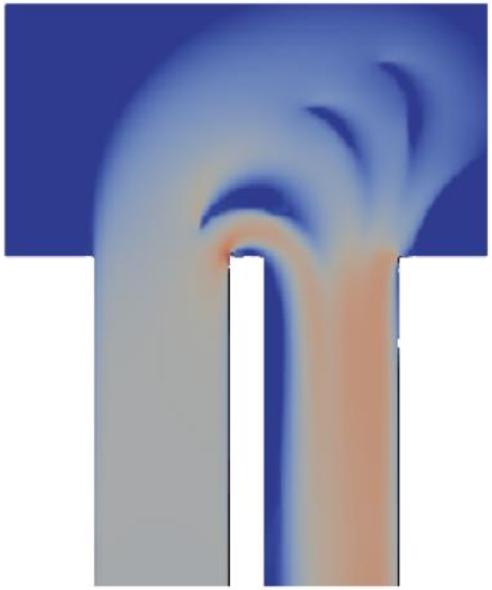
Results - Different Inlet Velocity

Inlet velocity :

6 m/s



17.5 m/s



Inlet Velocity	*Pressure Drop*	*Improvement*
6 *m/s*	~ 47%	~ 50%
17.5 *m/s*	~ 39%	~ 54%

Results - Different Inlet Velocity

Inlet velocity :

6 m/s

17.5 m/s

Filtered Geometry: the black region indicates the fluid region, i.e. the portion where the impermeability is low

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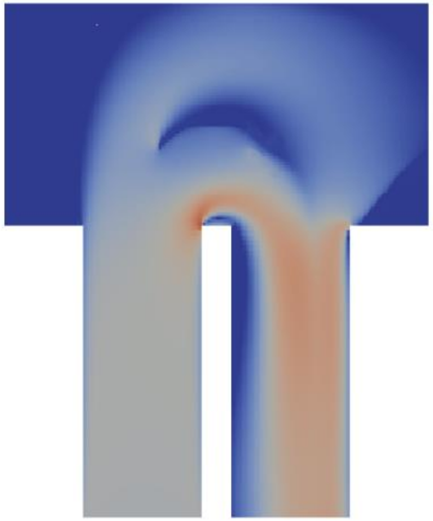
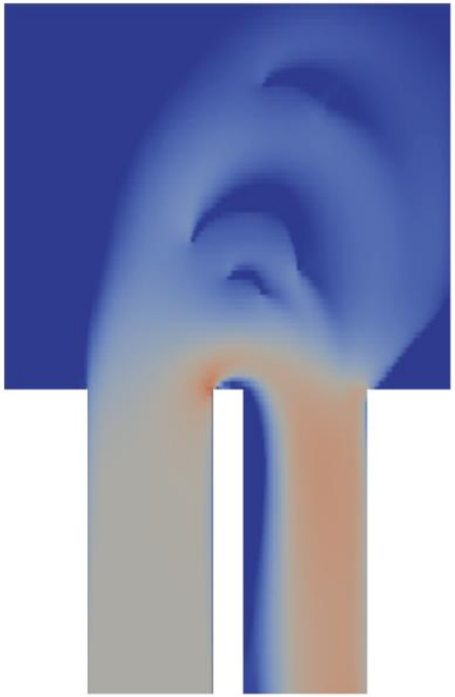
Results - Different Aspect Ratio

Aspect ratio (inlet vel. 17.5 m/s):

2:1



2:2



Aspect ratio	*Pressure Drop*	*Improvement*
2:1	~ 39%	~ 54%
2:2	~ 33%	~ 60%

Results - Different Aspect Ratio

Aspect ratio (inlet vel. 17.5 m/s):

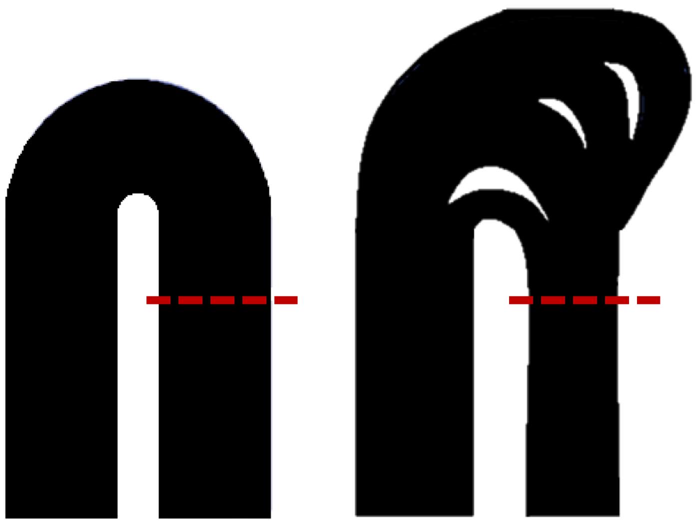
2:1

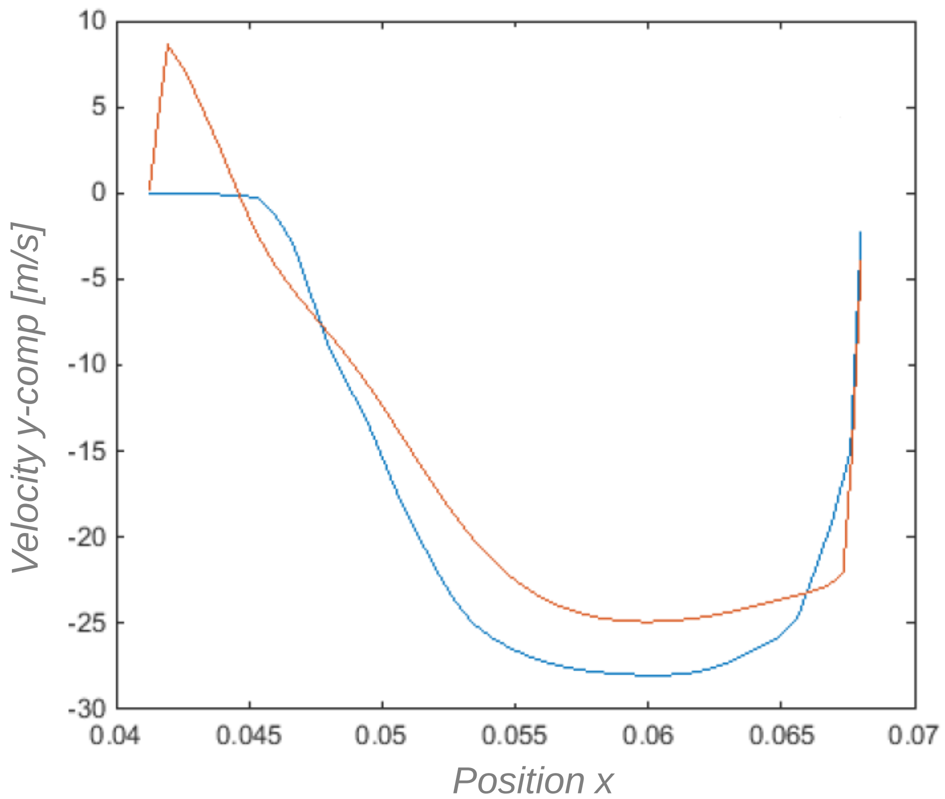
2:2

Filtered Geometry: the black region indicates the fluid region, i.e. the portion where the impermeability is low

Results – Velocity Profile

Velocity profile across the cutting red line for inlet velocity 17.5 m/s

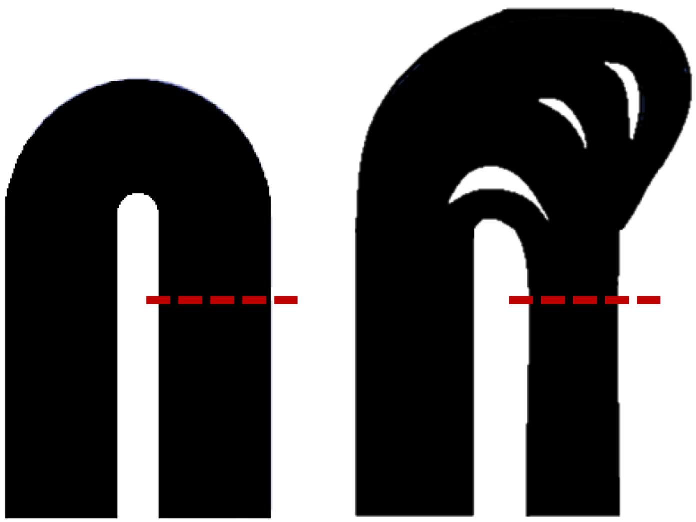


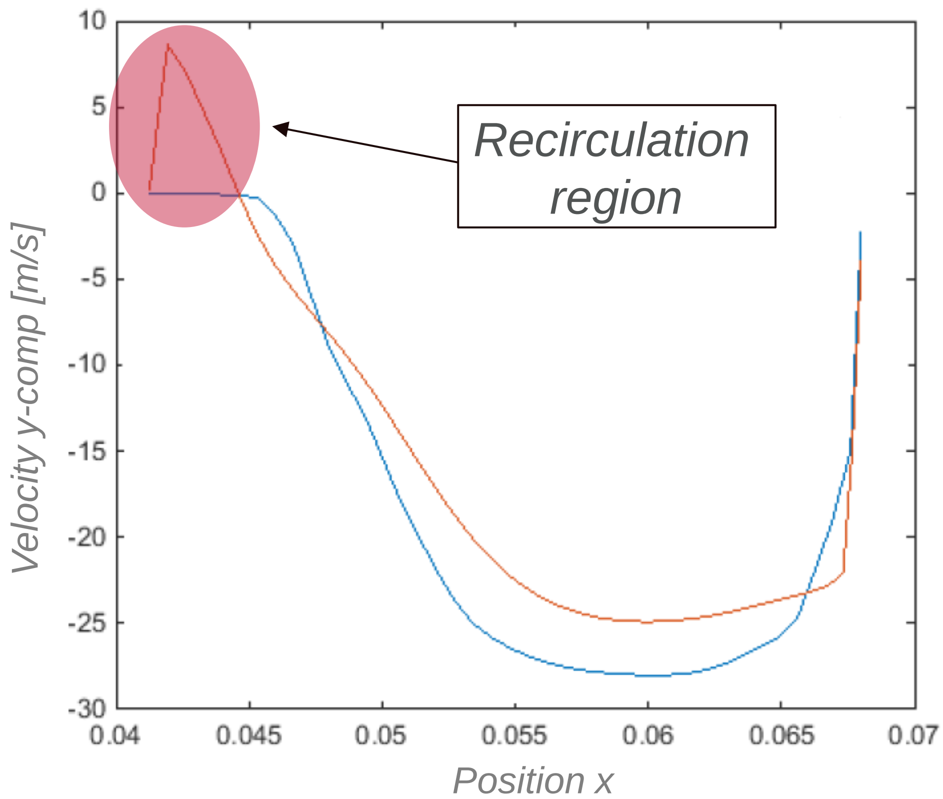


Standard geometry
Optimised geometry

Results – Velocity Profile

Velocity profile across the cutting red line for inlet velocity 17.5 m/s





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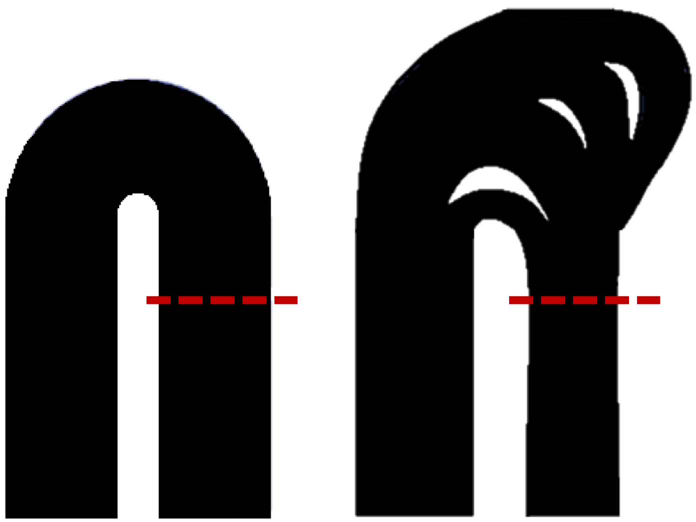
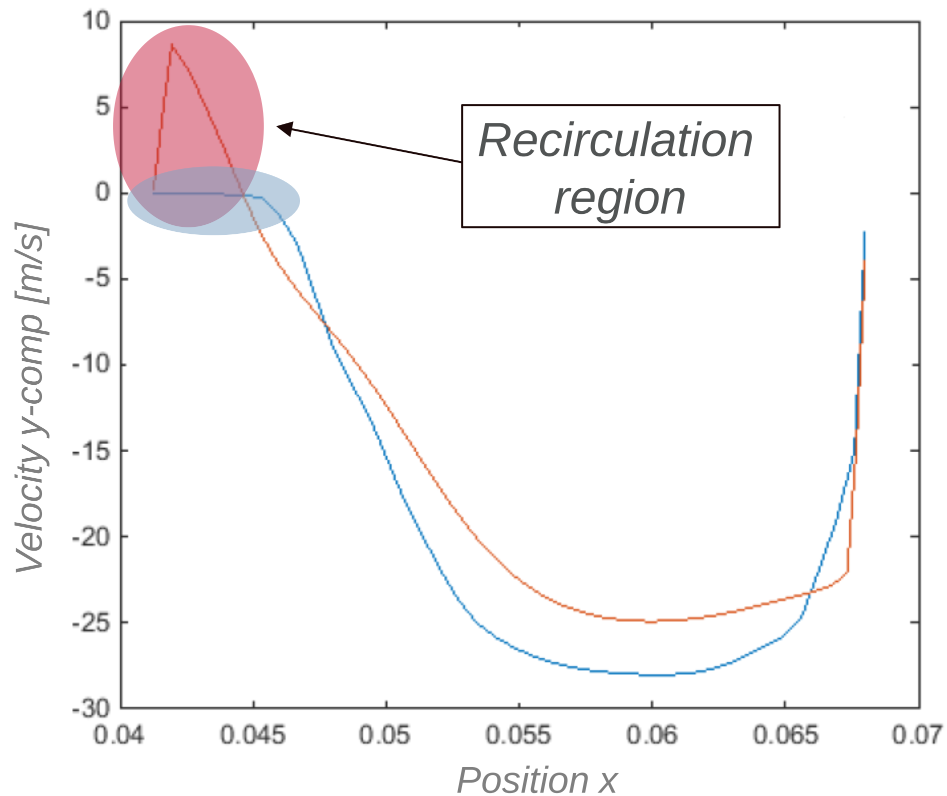


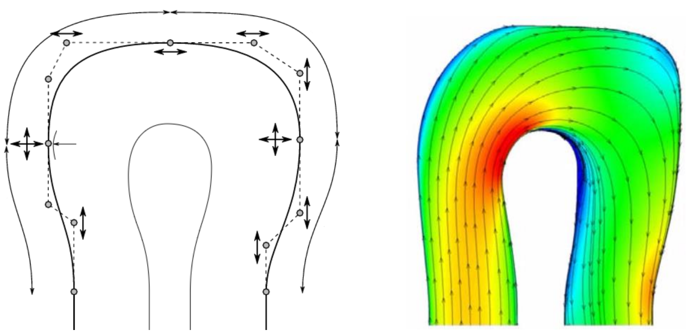


Standard geometry
Optimised geometry

TO and other Optimisation Methods

TO shows better performances compared to other optimisation methods

[T. Verstraete et al. GT2011 – 46541]



[Pietropaoli et al ASME IGTI 2017]

Method	*Improvement*
Genetic Alg. + Bezier parameter.	~ 37%
Adjoint Opt. + Boundaries Disp.	~ 37%
Adjoint Opt. + Bezier parameter.	~ 47%
Adjoint Opt. + TO (aspect ratio (2:1))	~ 54%
Adjoint Opt. + TO (aspect ratio (2:2))	~ 60%

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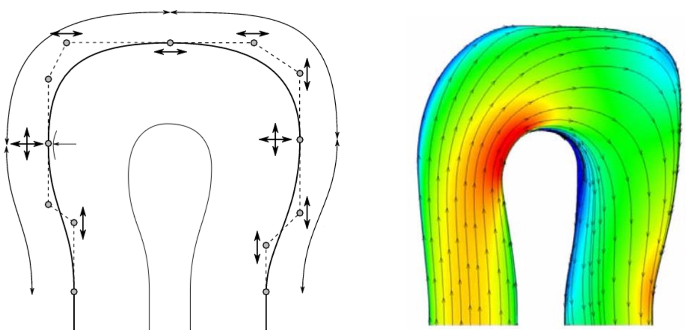

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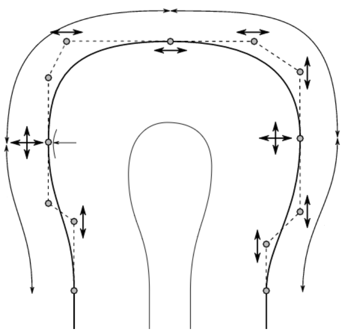
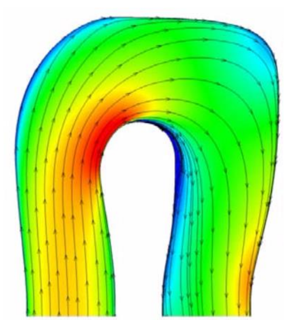
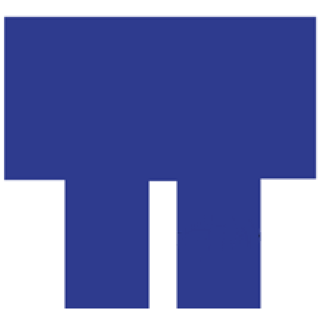




Shape Opt.
- 26 degree of freedom,
- ~100 CFD

[Pietropaoli et al ASME IGTI 2017]



Topology Opt.
- ~ 1 million degree of freedom,
- ~5x CFD

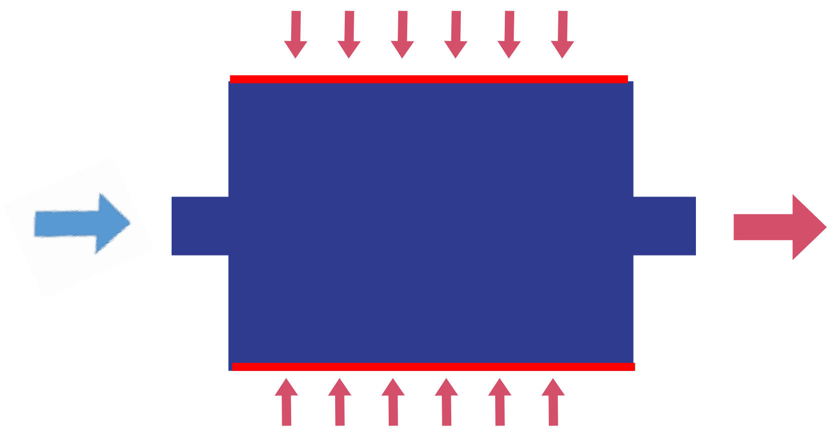
[T. Verstraete et al. GT2011 – 46541]

Can we add heat transfer?

Heat Transfer and TOffee

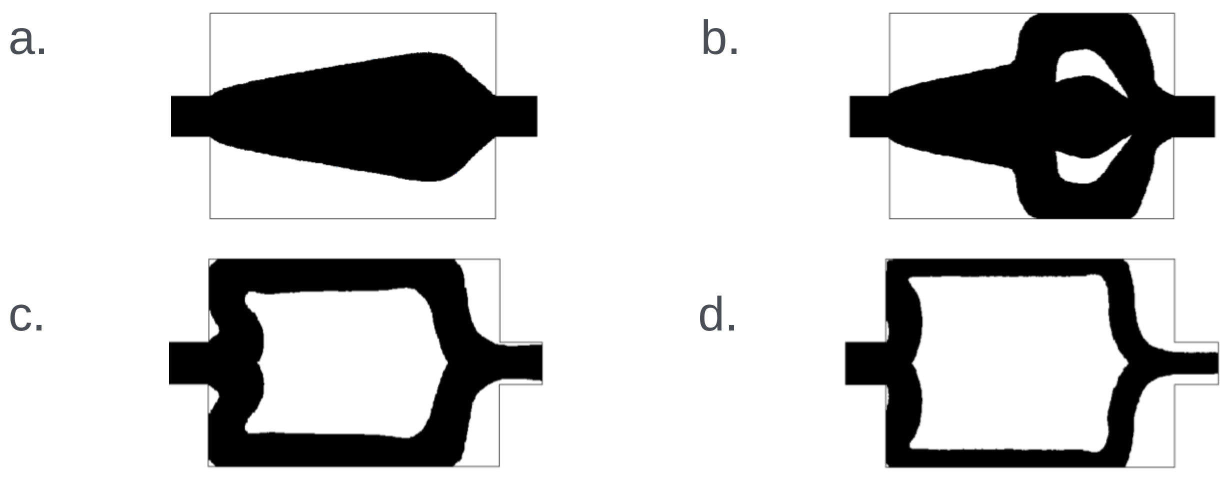
- *Energy equation for incompressible flow* $$v \cdot \nabla T = \frac{1}{\rho c} \nabla \cdot (k \nabla T)$$

- *Objective function: temperature gain of the flc* $$\int_{\Sigma} \rho c \; T \; v_n \;\; d\Sigma$$



2D results reducing losses and increasing HT

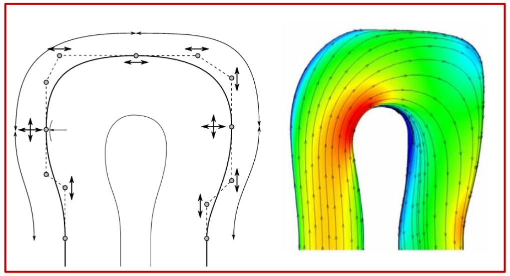
	Weights	Pressure drop	Temperature gain
a.	$\hat{\omega}_1 = 1, \hat{\omega}_2 = 0$	73.7%	8.4%
b.	$\hat{\omega}_1 = 0.995, \hat{\omega}_2 = 0.005$	88.5%	12.7%
c.	$\hat{\omega}_1 = 0.99, \hat{\omega}_2 = 0.01$	94.6%	41.0%
d.	$\hat{\omega}_1 = 0.9, \hat{\omega}_2 = 0.1$	96.1%	49.7%

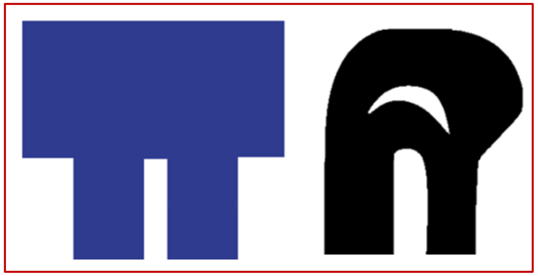


[M. Pietropaoli et al. GTP 16 – 13

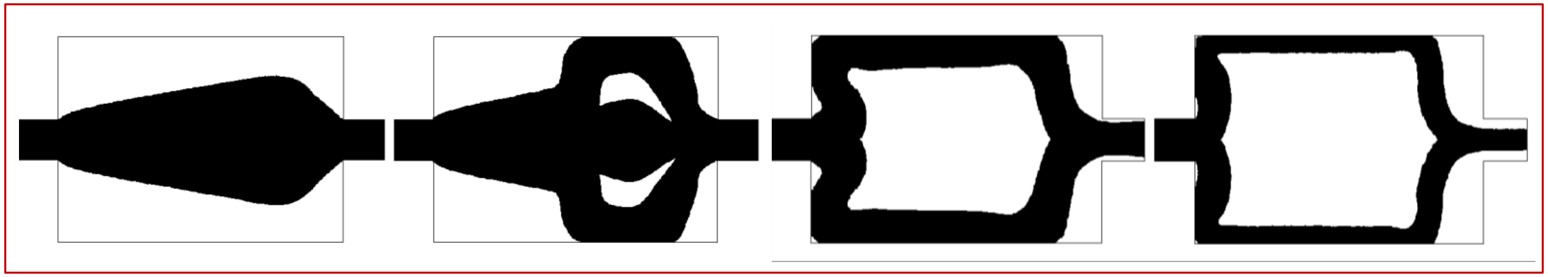
Recap (quick)

- *Pressure losses: optimisation of U – Bend. TOffee shows an improvement up to 60% higher than shape optimisation performed by VKI*



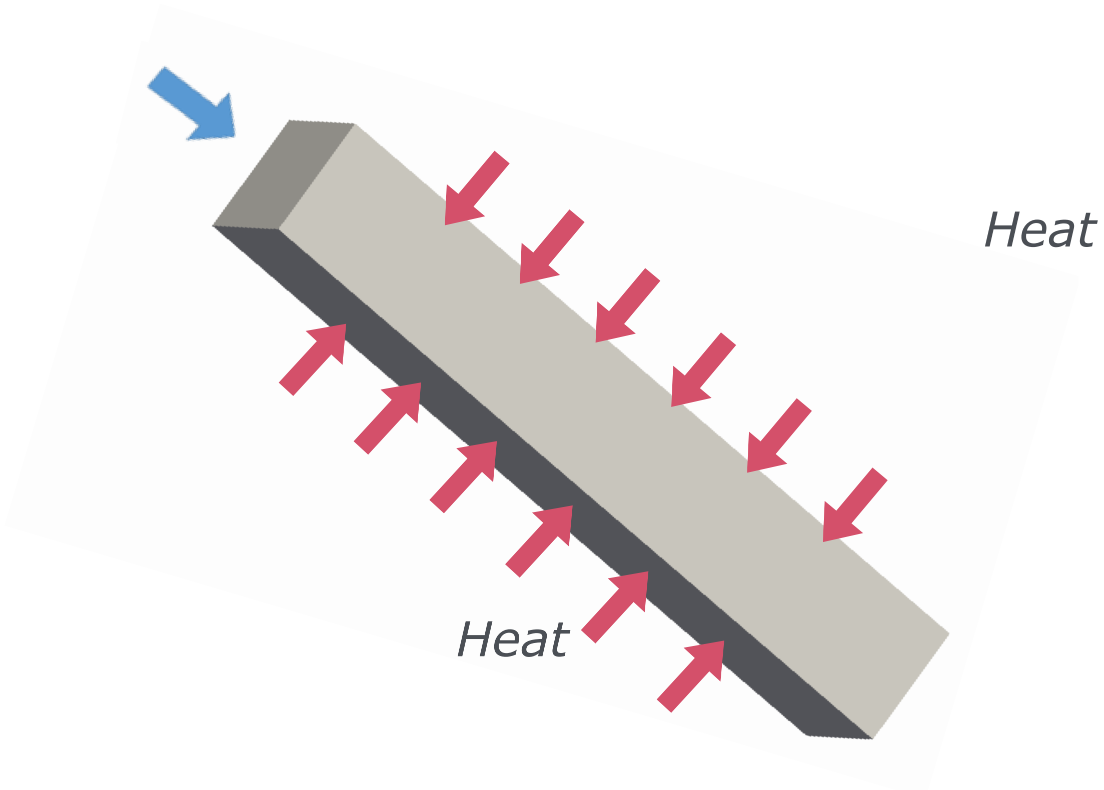


- *Heat transfer: main instability issues have been fixed. 2D results*



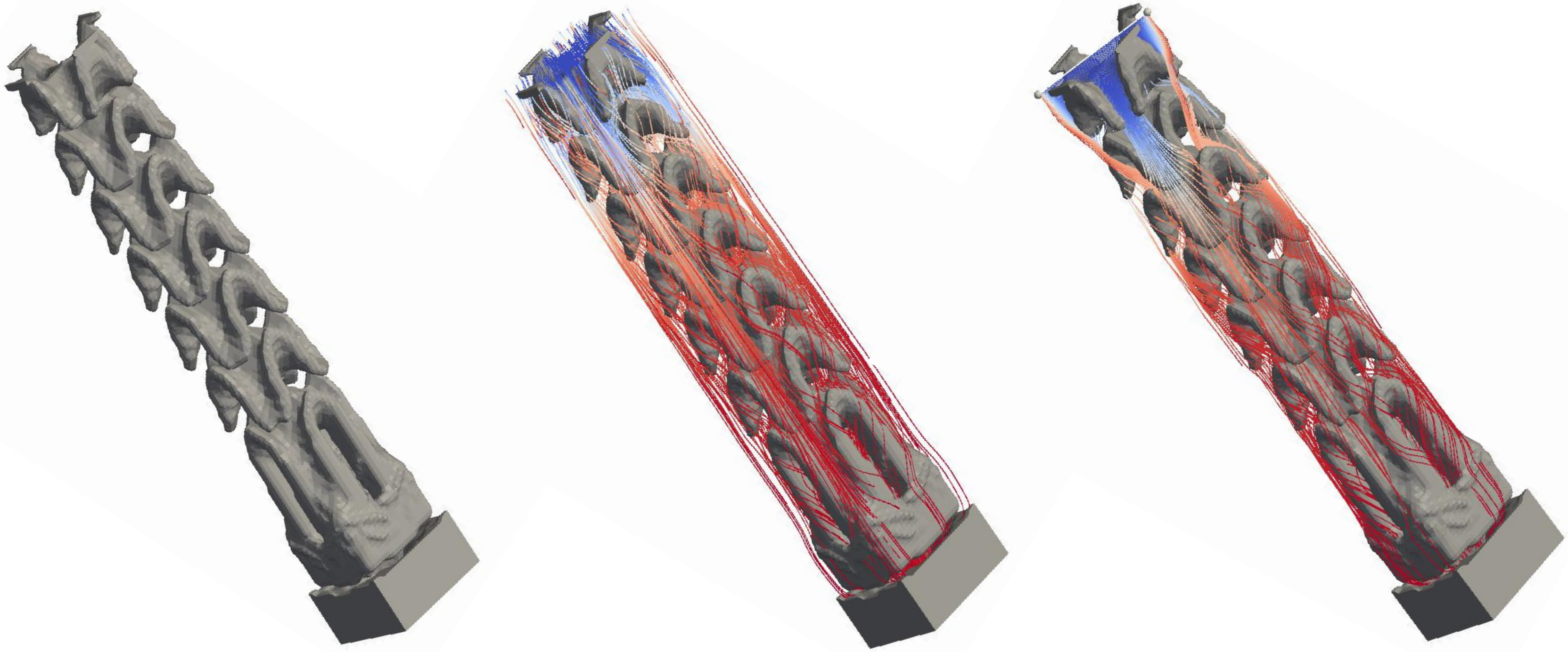
3D?

- *Squared duct test case*



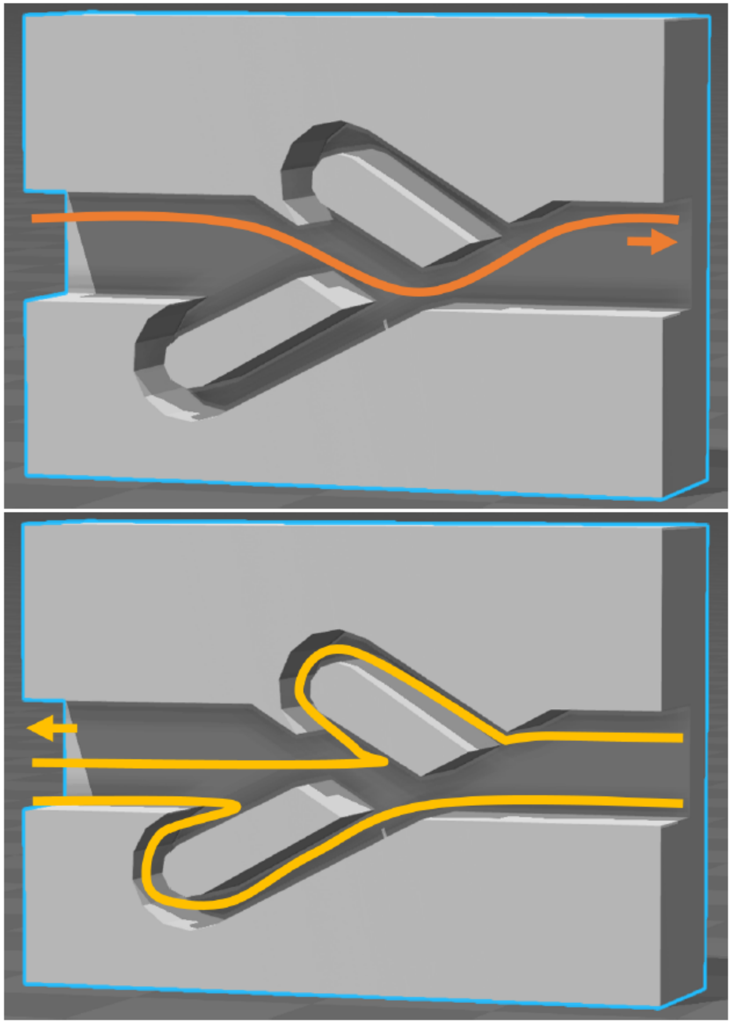
solution

- *Velocity streamlines generated from the inlet*



Can we build valves without moving parts?

Valves without moving parts?



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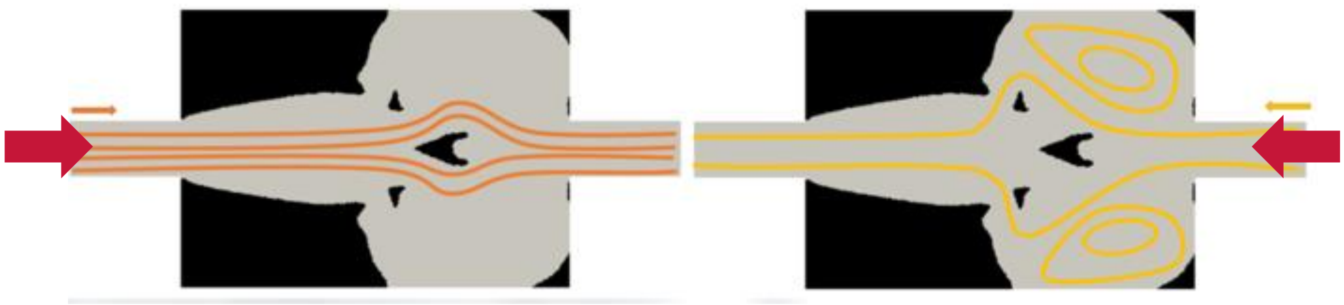
Valves without moving parts?

Designed by TOffee….



Robust Solutions

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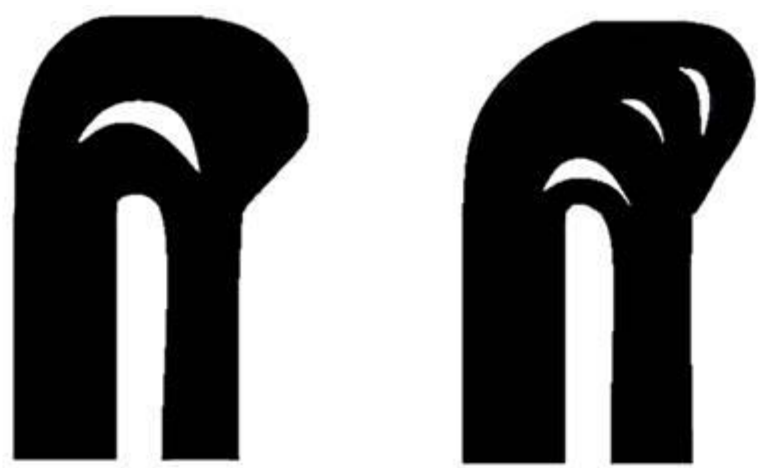
Problem 1: Solution dependent on BCs

Changing BCs gives different results/designs

Example:



GT2018-75761 *Robust Topology Optimization Using Polynomial Chaos Expansions: TOffee, A.Gaymann, F.Montomoli, M.Pietropaoli*

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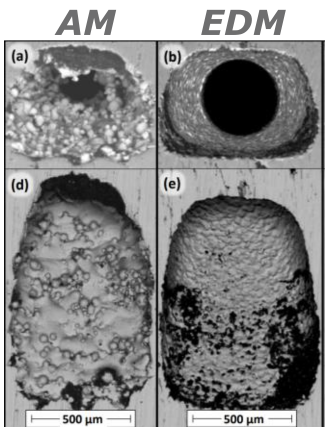
Problem 2: AM geometries affected by errors

AM surface roughness impact experimental results

We are not explaining here how to do it



[Effectiveness Measurements of Additively Manufactured Film Cooling Holes]

Paper: GT2017-64903; Author(s): Curtis K. Stimpson, Jacob C. Snyder, Karen A. Thole, Dominic Mongillo

Problem Statement

Is it possible to tackle uncertainties in the BCs during TO?

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Boundary Conditions

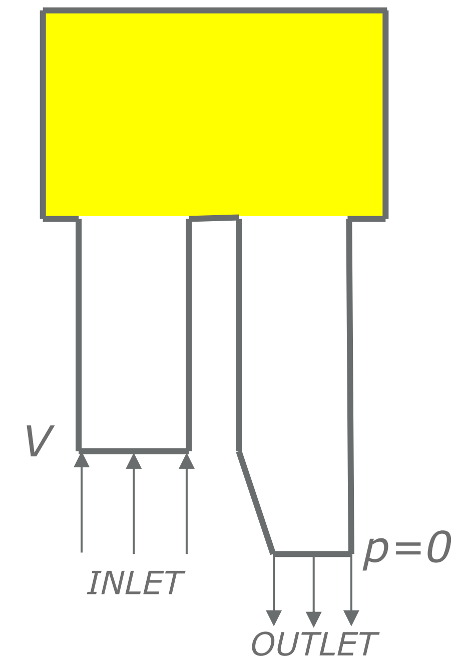
Inlet: uniform distribution velocity:

$$V = [V_{min}, V_{max}]$$

Outlet : atmospheric pressure

Wall boundaries everywhere else

Yellow volume given to the optimizer



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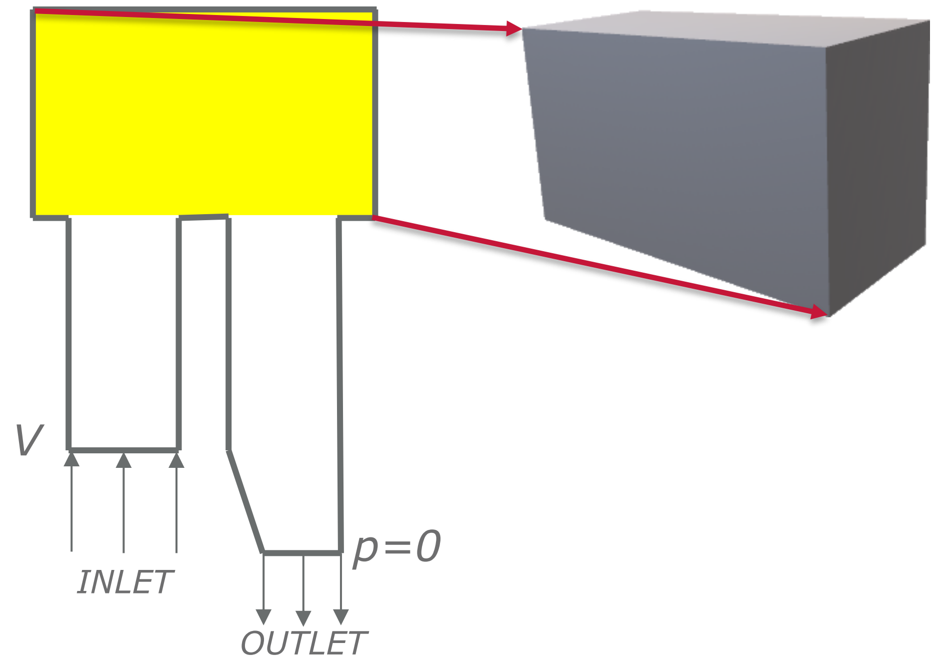
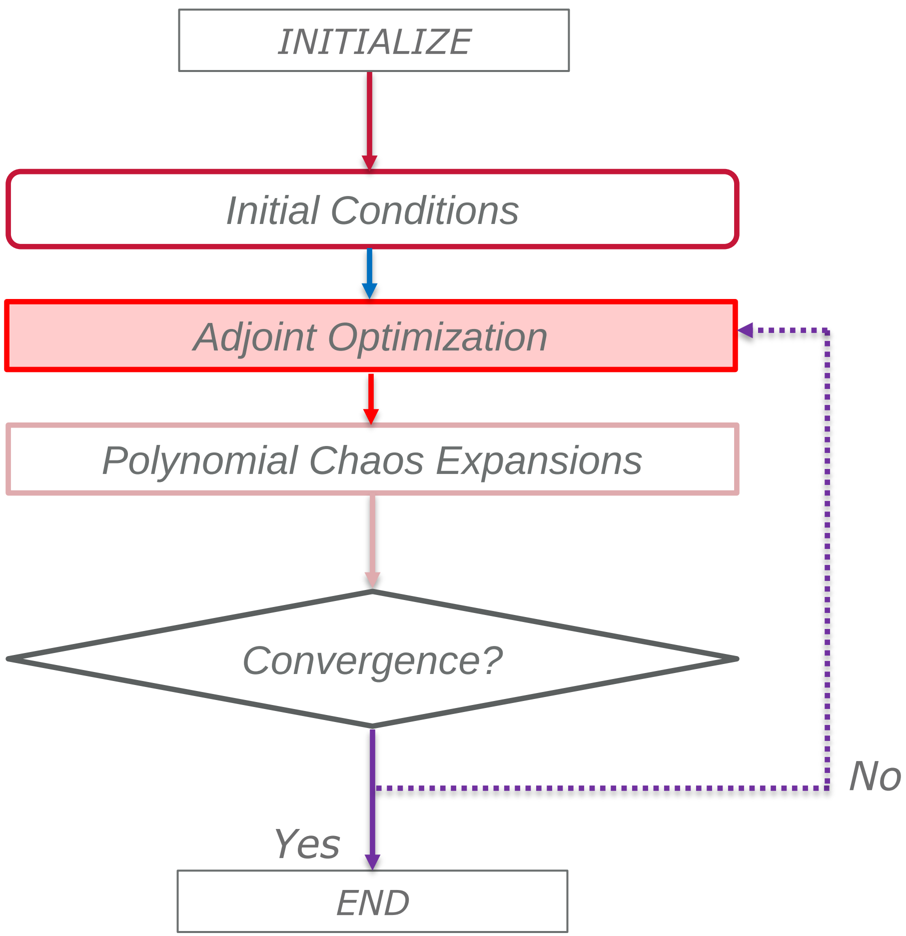
Boundary Conditions

Optimizer is inherently 3D

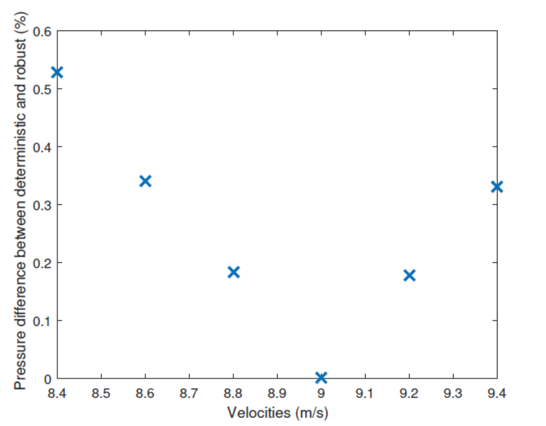
2D obtained with one layer in the third spatial dimension

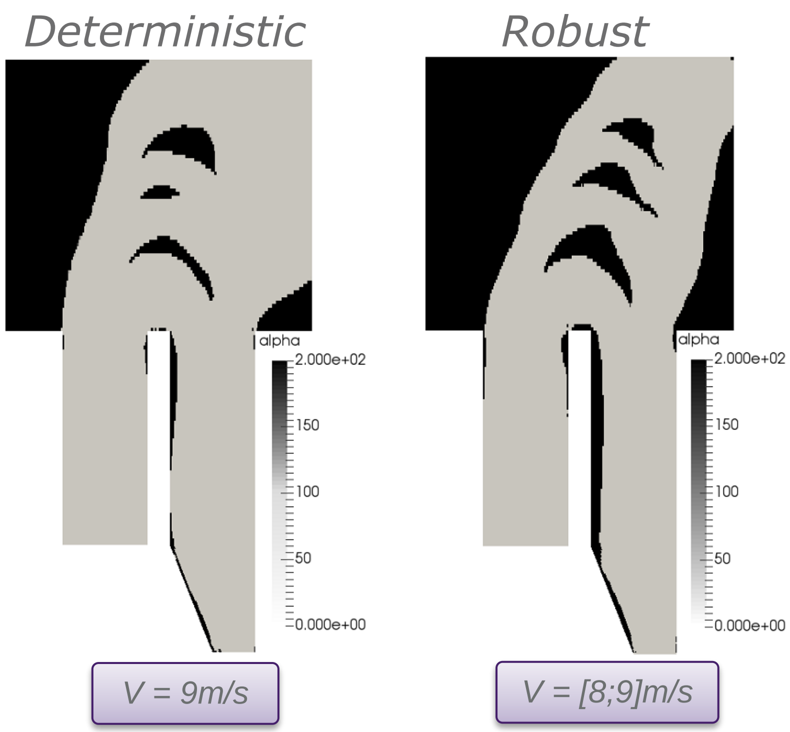


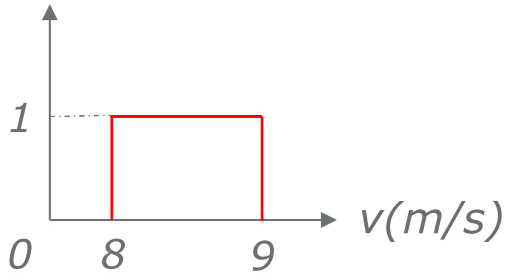
Governing equations - Polynomial Chaos Expansions



Results

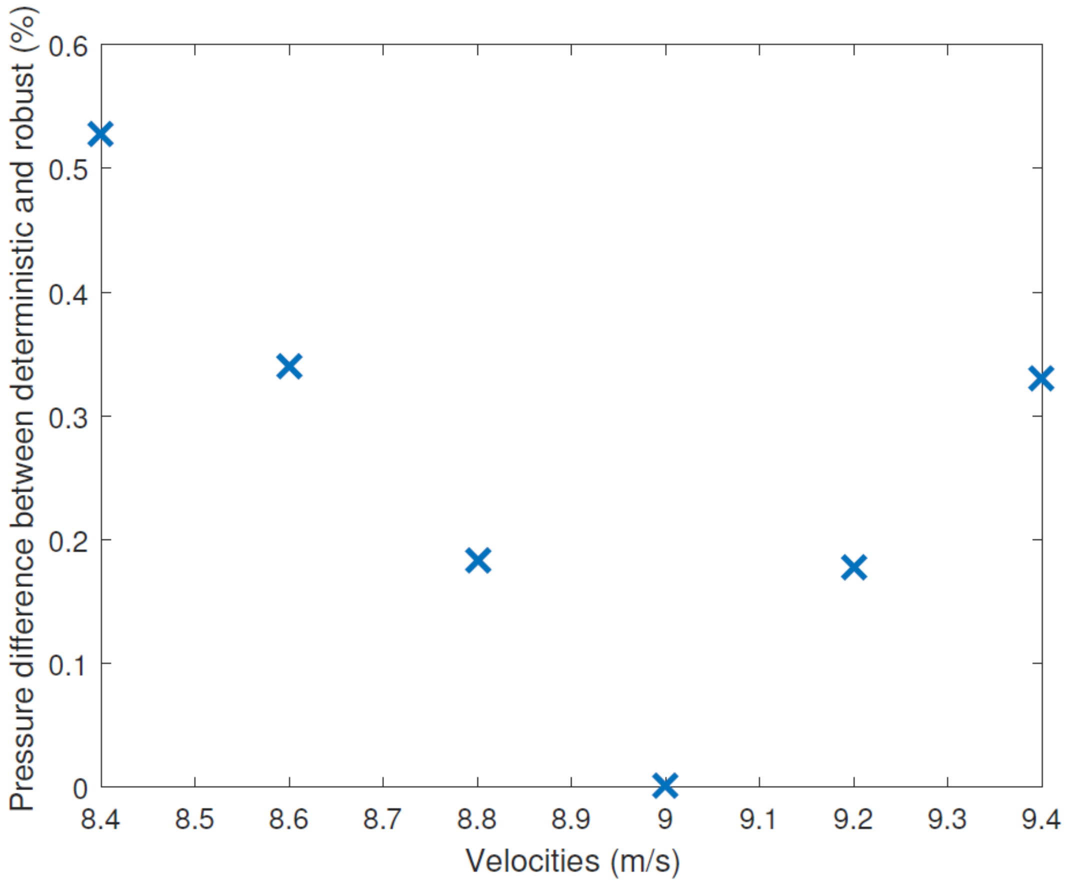






GT2018-75761 *Robust Topology Optimization Using Polynomial Chaos Expansions: TOffee, A.Gaymann, F.Montomoli, M.Pietropaoli*

Robust Results



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Conclusions

- *Additive Manufacturing for the production of complex mechanical components for coolant systems*

- *Fluid Topology Optimisation is the way to exploit the flexibility of AM*

- *We have a framework to solve such problem*

- *SO vs TO: fluid TO less cost*