Technical perfection, automotive passion

faurecia

Emissions Control
Technologies

Application
of a
Continuous Adjoint Flow Solver
for
Geometry Optimisation
of
Automotive Exhaust Systems

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FLOWHEAD Workshop, Varna • Sept. 2010

Workshop on industrial design optimisation for fluid flow

Abstract

Meeting backpressure and flow uniformity requirements within severe packaging constraints presents a particular challenge in the layout of catalyst inlet cones. In these cases, a parameterized optimization of the potentially complex cone geometries is inefficient (and inappropriate). Even assuming that a parameterization of the complex surface forms is possible, the choice of parametric shapes invariably affects the achievable results. Additionally, the long computation time for solving the flow fields limits the number of shape parameters that can be considered.

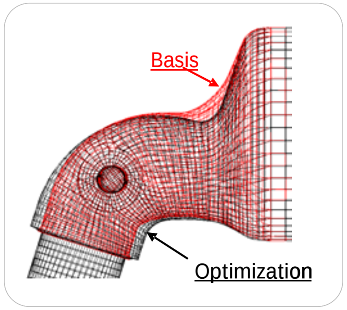
To overcome these restrictions, an optimization tool has been developed at Faurecia Emissions Control Technologies [1] that is based on the continuous adjoint formulation derived and implemented by C. Othmer et al [2, 3]. The open source CFD toolbox OpenFOAM® is used as the platform for the implementation. Since the geometry itself is modelled using an immersed boundary method, no geometry parameterization is required. The method allows computation of the sensitivity of flow uniformity and energy dissipation (or other target quantities) based on the instantaneous geometry. After the calculated surface sensitivities are combined and corrected for manufacturing and topological constraints, the location of the immersed boundary is automatically adjusted. It is thus possible to automatically determine a feasible catalyst cone geometry starting from an amorphous box (representing the packaging constraints) that is supplemented by definitions of inflow boundaries (for the flow coming from different manifold runners) and the outflow boundary (the catalyst surface). The calculation time associated with the process is on the same order of magnitude as the solution of the RANS equations itself. The optimization tool and some practical results will be presented.

[1] C. Hinterberger, M. Olesen, "Automatic geometry optimization of exhaust systems based on sensitivities computed by a continuous adjoint CFD method in OpenFOAM", SAE 2010-01-1278
[2] C. Othmer, E. de Villiers and H.G. Weller
"Implementation of a continuous adjoint for topology optimization of ducted flows", AIAA-2007-3947
[3] C. Othmer, "A continuous adjoint formulation for the computation of topological and surface sensitivities of ducted flows", Int. J. Num. Meth. Fluids, 2007

Outline

Optimization of Catalyst-Cone

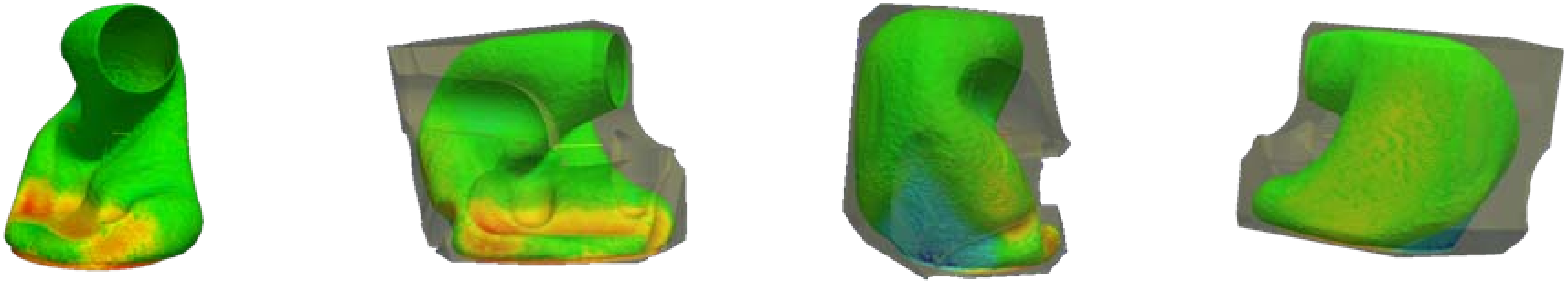
- ➢ reduce back pressure
- ➢ Improve flow uniformity at catalyst



OpenFOAM® based CFD solver

- ➢ CAGO (Continous Adjoint Geometry Optimisation)

Application Examples



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Motivation

Challenge for the CFD-engineer:

„find optimal geometry of catalyst inlet cone !“

- good flow distribution + low pressure drop
- suitable for production, costs, development time, ...

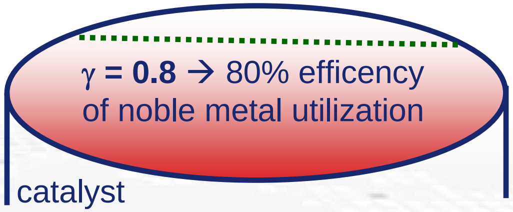
Mathematical problem description:

„optimize objective function $J(\gamma, \Delta p, \ldots)$ “

Δp ... pressure drop
(fuel consumption)

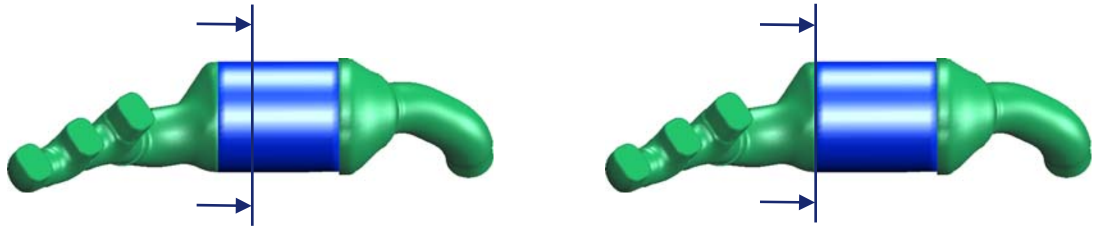
γ ... flow uniformity index
(noble metal cost, emission standards)

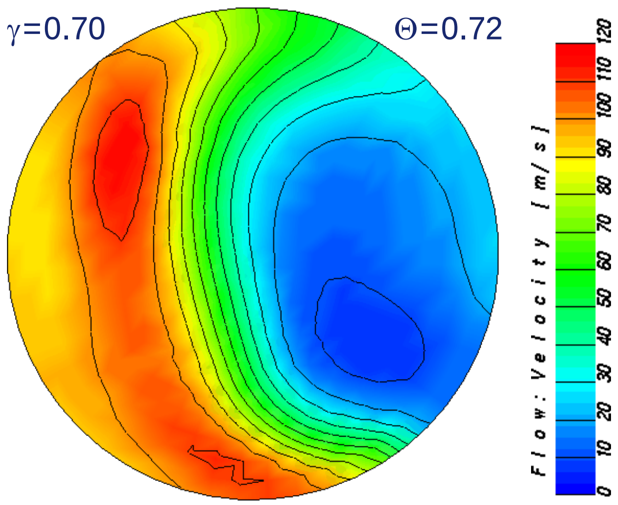
$$\gamma = 1 - \frac{1}{2A\bar{v}_n}\int_{cat} \left| v_n - \bar{v}_n \right| dA$$



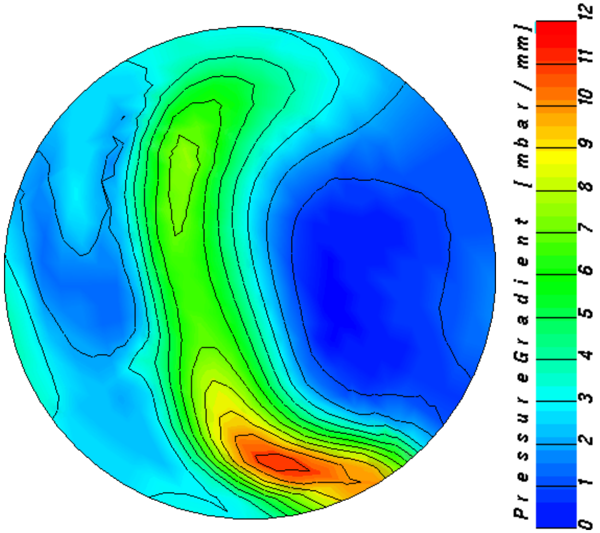
γ = 0.8 → 80% efficency
of noble metal utilization

Optimization of Catalyst-Cone

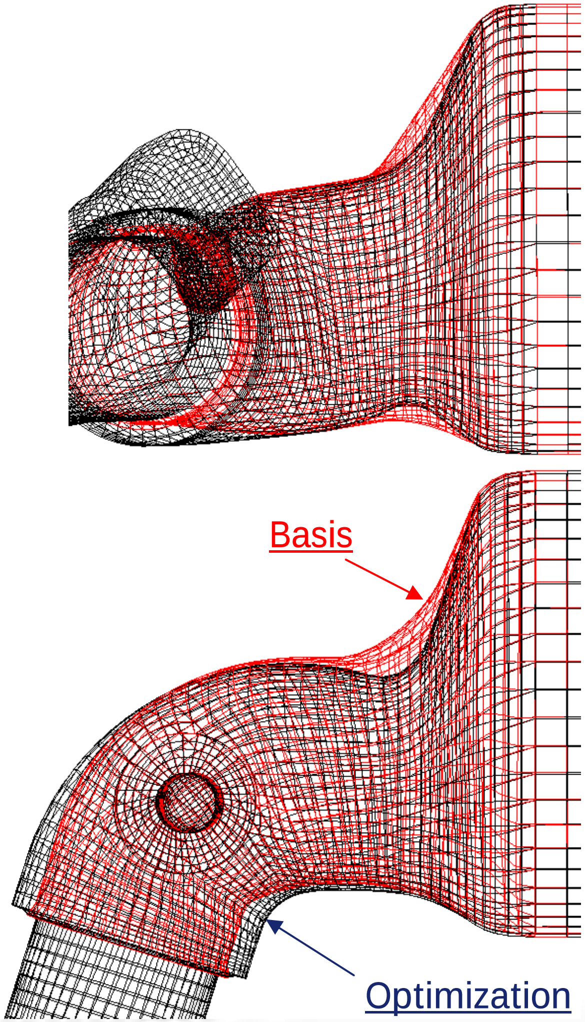




v_max=117 m/s

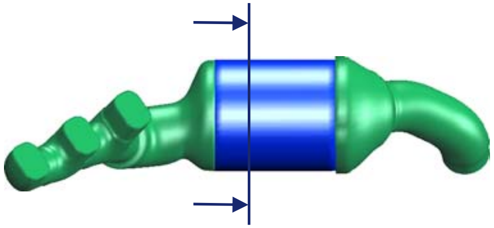


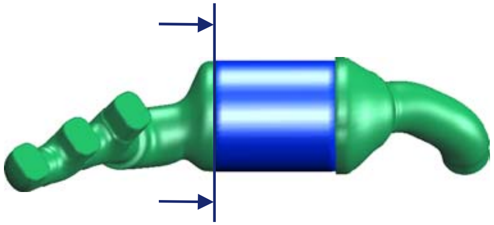
dp/dx_max=11 bar/m



basic configuration

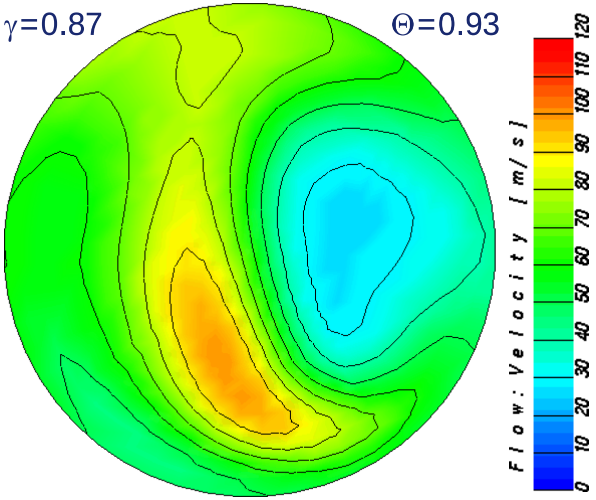
Optimization of Catalyst-Cone



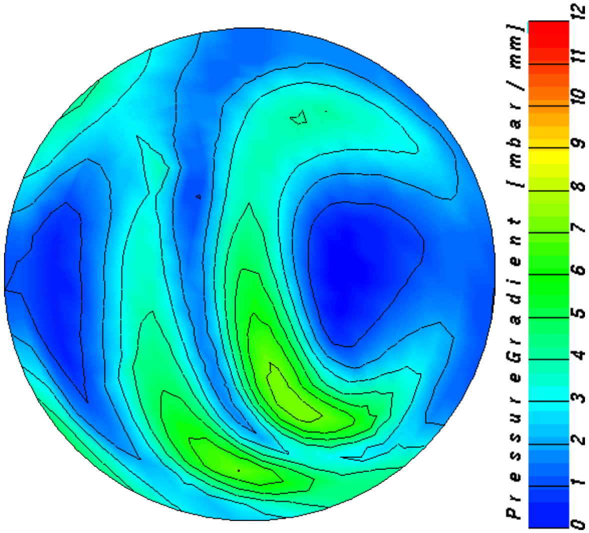


γ=0.87

Θ=0.93

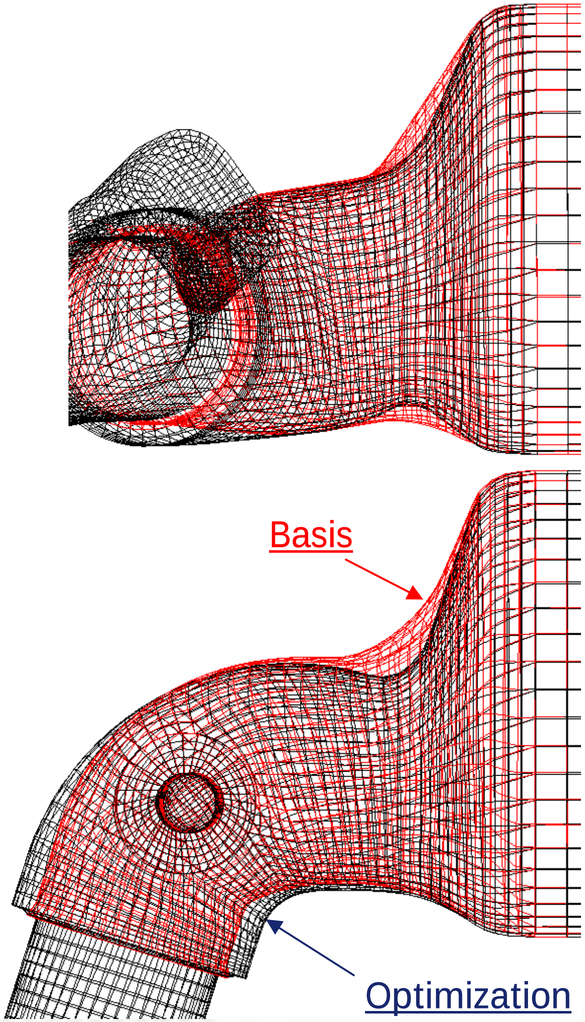


v_max=100 m/s



dp/dx_max=7 bar/m

optimized configuration



Main problem: „ How to change the geometry? “

geometry modification ?

analytical solution

experience

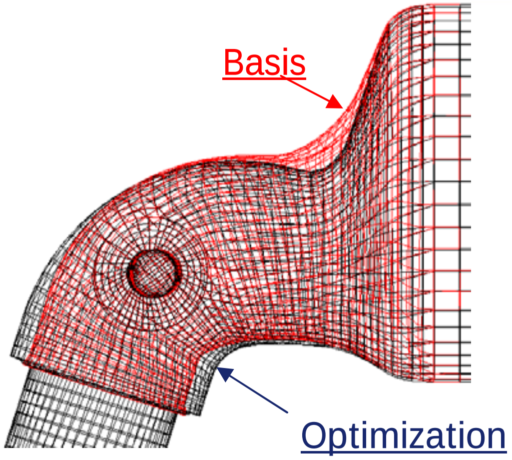
trial and error

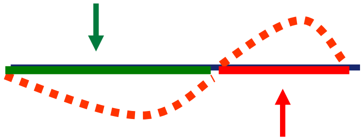
sensitivities $\partial J / \partial_{geom}$

geometry parameterization
+ DOE, RSM
→ automatic optimizer

Adjoint Method

Finite Differences
Automatic Differentiation





OpenFOAM® based solver CAGO (Continuous Adjoint Geometry Optimisation)

Starting Point

- OpenFOAM-solver from C. Othmer, H. Weller, E. de Villiers

  Implementation of a continuous adjoint for topology optimization of ducted flows , AIAA-2007-3947
- theory paper from C. Othmer

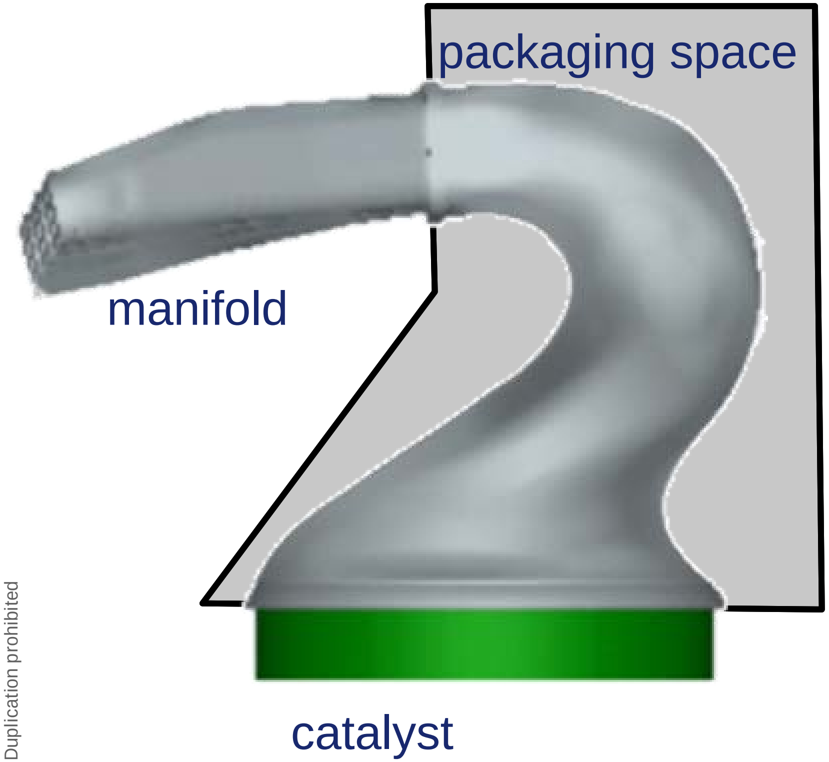
  A continuous adjoint formulation for the computation of topological and surface sensitivities of ducted flows , Int. J. Num. Meth. Fluids, 2008

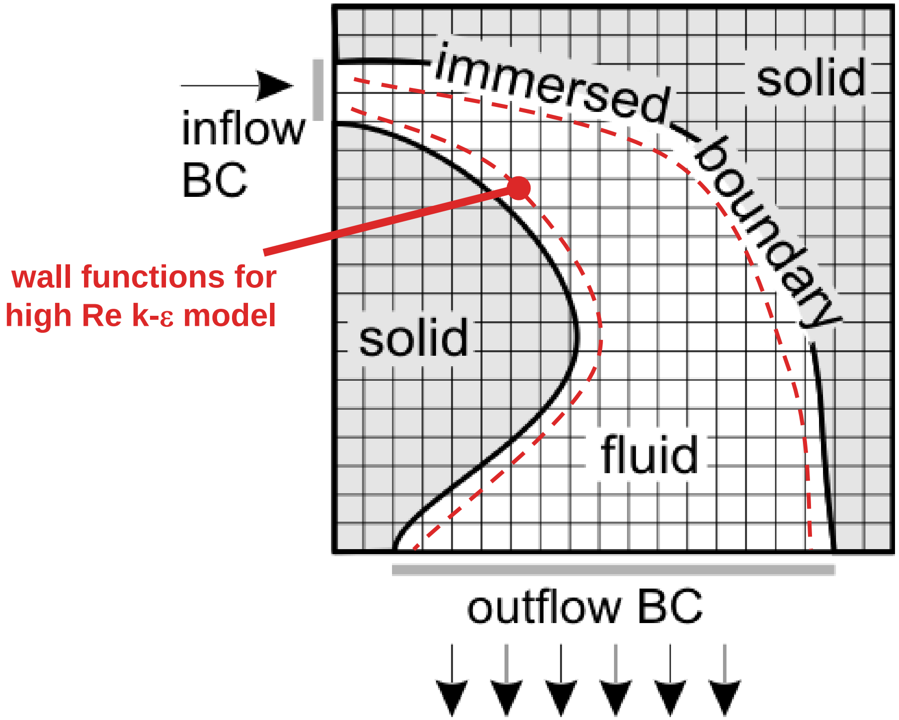
Modifications

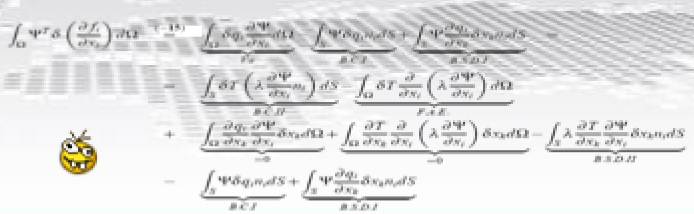
- topology conserving geometry variations
- discrete fluid/solid distinction
- wall functions at fluid/solid-interface
- multiple adjoint flow fields (pressure drop, uniformity & centricity)
- multiple flow fields (different ports of naturally aspirated engine)

- details can be found in SAE paper 2010-01-1278

CFD model


packaging space
manifold
catalyst


inflow
BC
wall functions for
high Re k-ε model
immersed boundary
solid
solid
fluid
outflow BC



Flow equations

NSE

momentum : $(\mathbf{u} \cdot \nabla)\,\mathbf{u} = -\nabla p + \nabla\cdot(\,\nu\,(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)\,)$

continuity : $\nabla\cdot\mathbf{u} = 0$

Adjoint

> Life can only be understood **backwards**;
> but it must be lived **forwards**. *(Søren Kierkegaard)*

Adj. momentum: $-\,(\nabla\mathbf{u}^* + (\nabla\mathbf{u}^*)^T)\cdot\mathbf{u} = -\nabla p^* + \nabla\cdot(\,\nu\,(\nabla\mathbf{u}^* + (\nabla\mathbf{u}^*)^T)\,)$

convection in upstream direction !

adjoint strain rate

Adj. continuity: $\nabla\cdot\mathbf{u}^* = 0$

Implementation of Momentum Eqn. in OpenFOAM

```
NSE:       fvm::div(  phi, v)                                + turbulence->divDevReff(u)    ==  -fvc::grad(p)
Adjoint:   fvm::div(- phi, u*) - fvc::grad(u*) & u + turbulence->divDevReff(u*)  ==  -fvc::grad(p*)
```

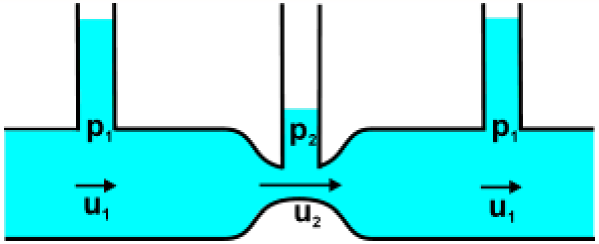
H. Weller, E. de Villiers, C. Othmer (AIAA-2007-3947)

Examples

Simple 2D Cases

example 1)
flow from the side –> analytical solution

Bernoulli-flow



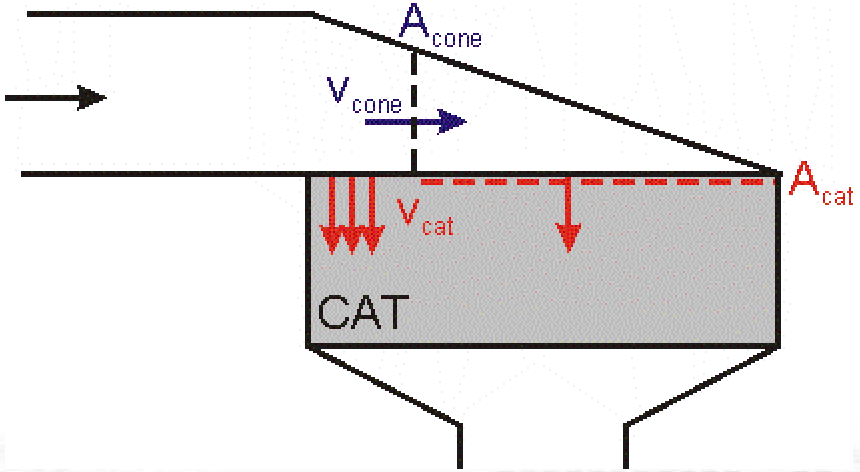
$$p_{total} = p_{static} + p_{dynamic} = const.$$

$$p_{dynamic} = \rho/2\, v^2$$

Catalyst Cone

$$\boxed{v_{cat} = const.} \Rightarrow p_{static} = const. \Rightarrow p_{dynamic} = \rho/2\, v_{cone}^2 = const.$$

$$\Rightarrow v_{cone} = const.$$



$$\dot{m}_{cone} = \dot{m}_{cat}$$

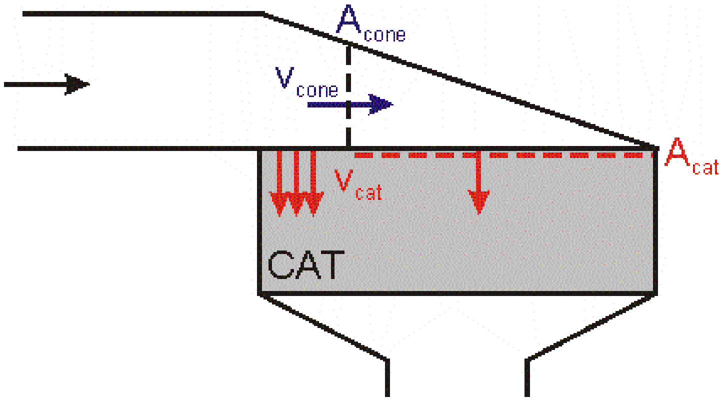
$$\dot{m}_{cone} = \rho A_{cone} v_{cone}$$

$$\dot{m}_{cat} = \rho A_{cat} v_{cat}$$

$$A_{cone} = A_{cat} v_{cat} / v_{cone}$$

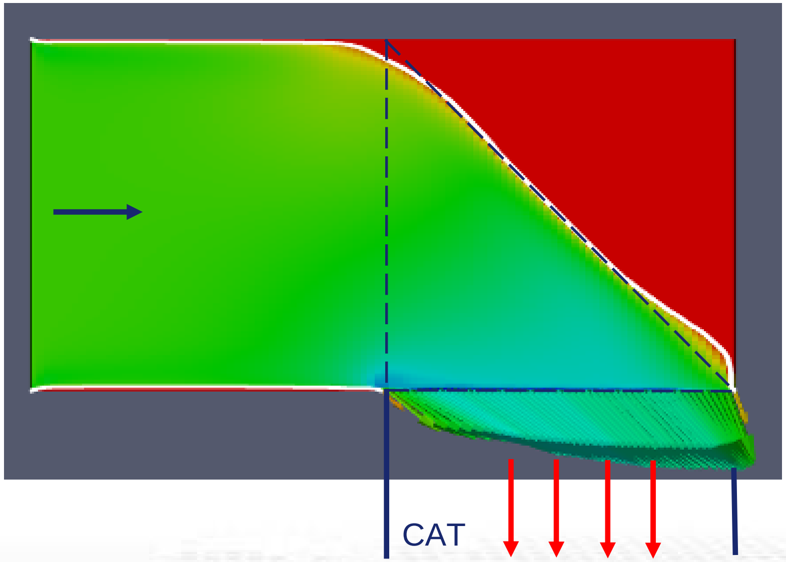
$$\Rightarrow \boxed{A_{cone} \sim A_{cat}}$$

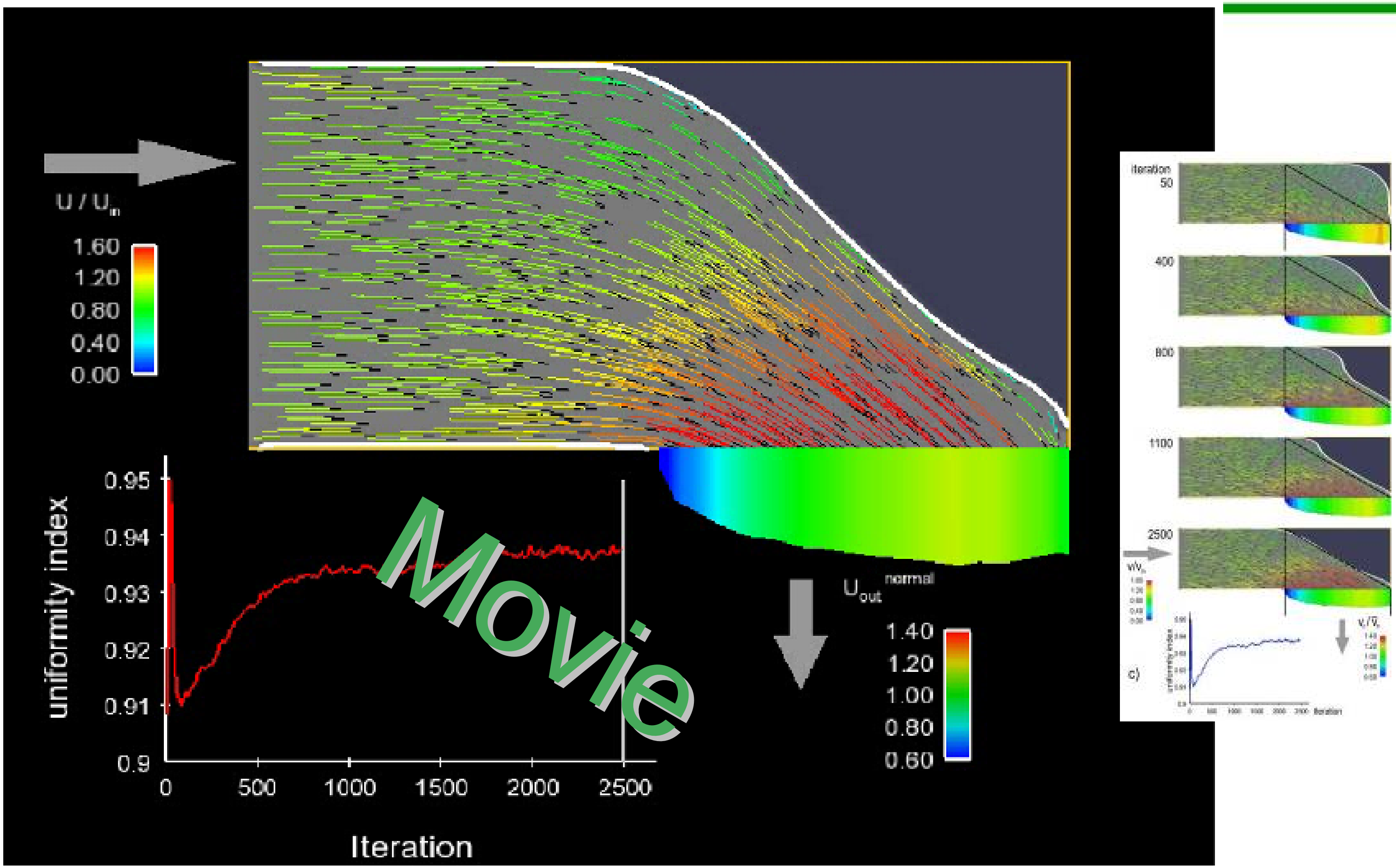
Analytical Solution



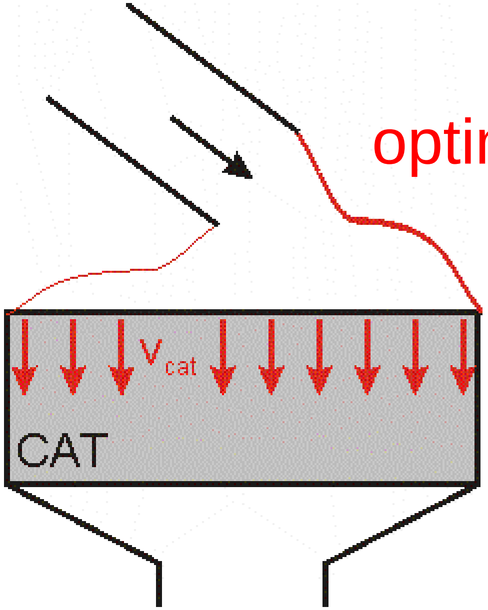
$$\boxed{A_{cone} \sim A_{cat}}$$

Adjoint Method



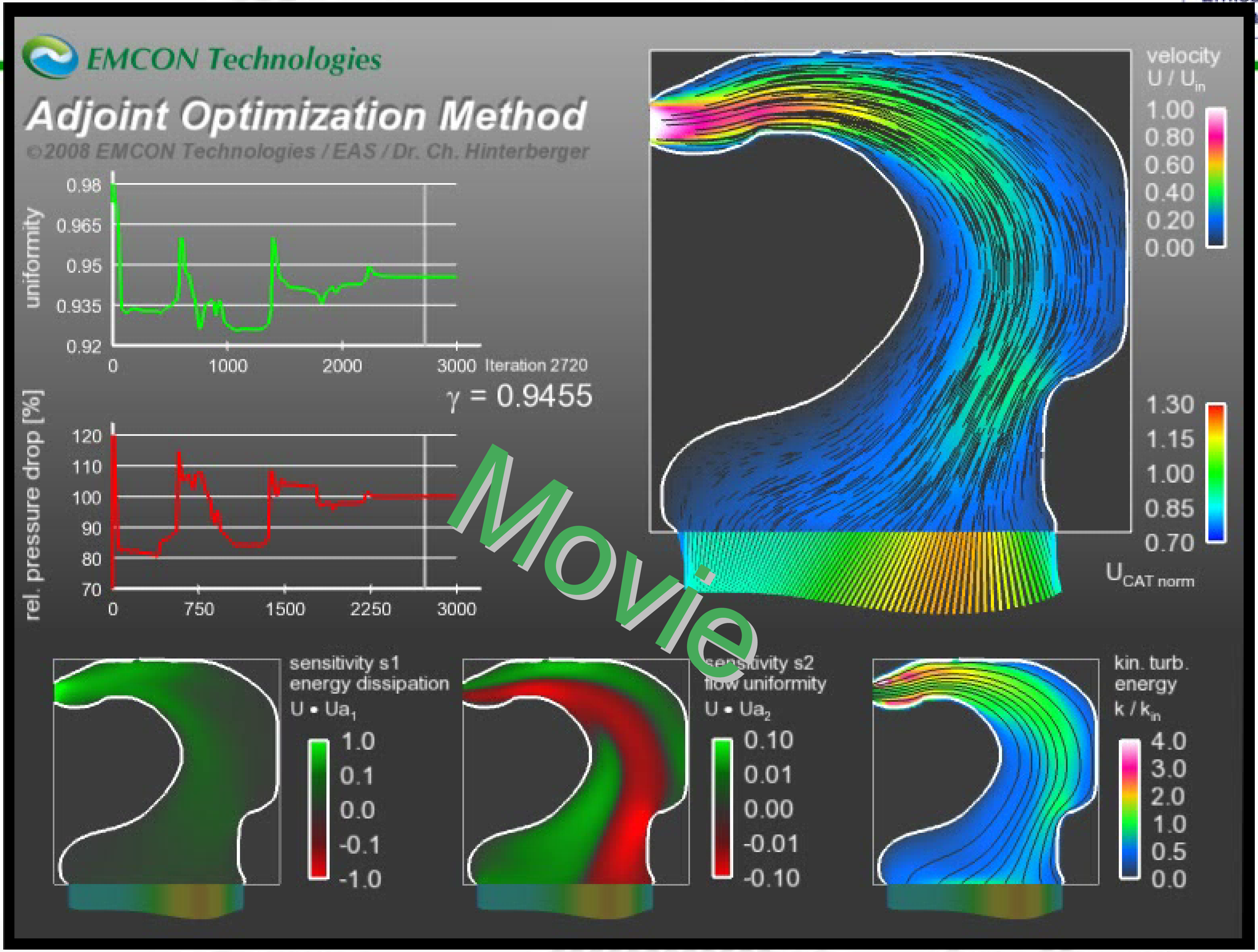

U / U_in
1.60
1.20
0.80
0.40
0.00
uniformity index
0.95
0.94
0.93
0.92
0.91
0.9
0
500
1000
1500
2000
2500
Iteration
Movie
U_out normal
1.40
1.20
1.00
0.80
0.60
iteration
50
400
800
1100
2500
c)

example 2) unsuitable inflow



optimal shape ?

→ solution: Adjoint Method



EMCON Technologies

Adjoint Optimization Method

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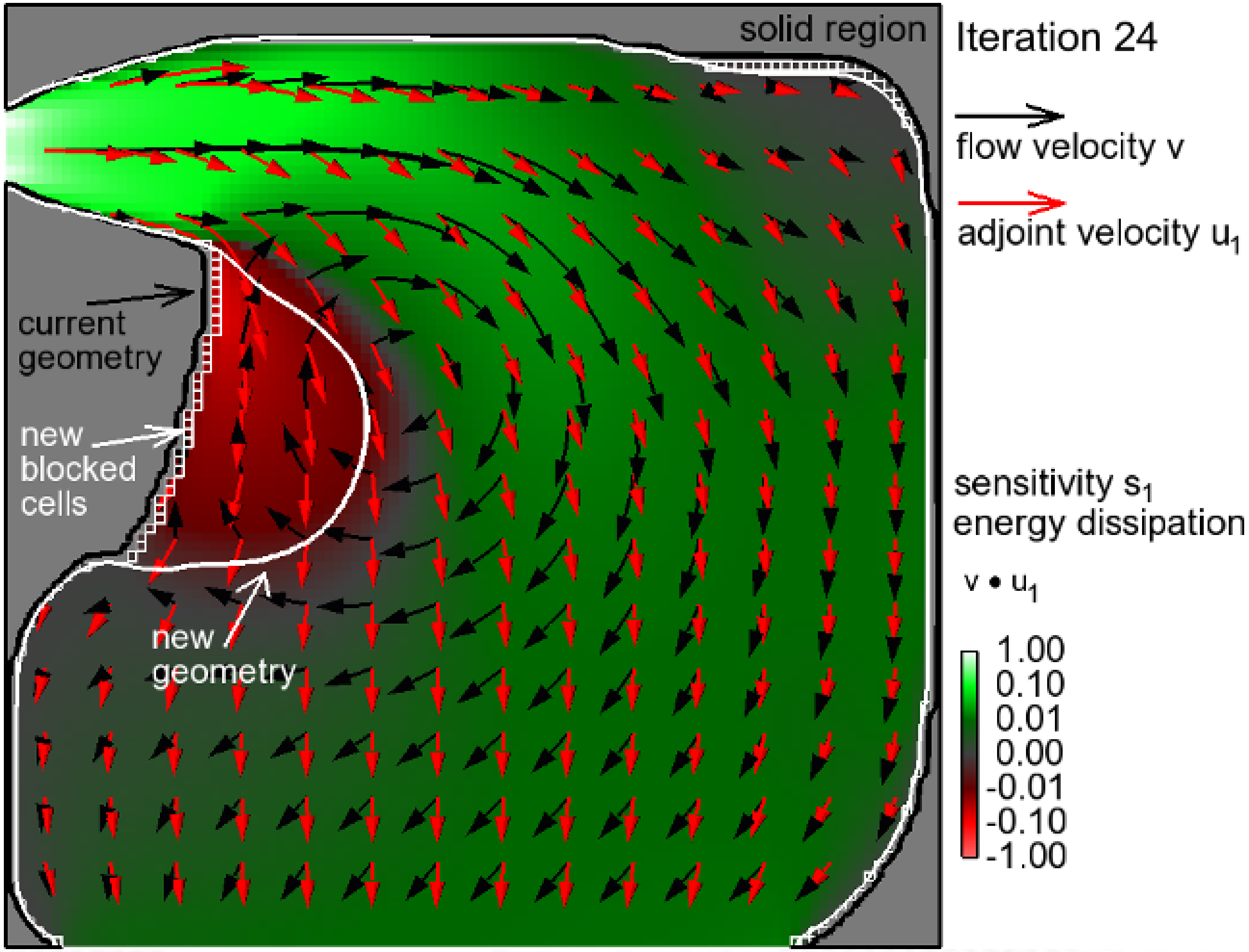
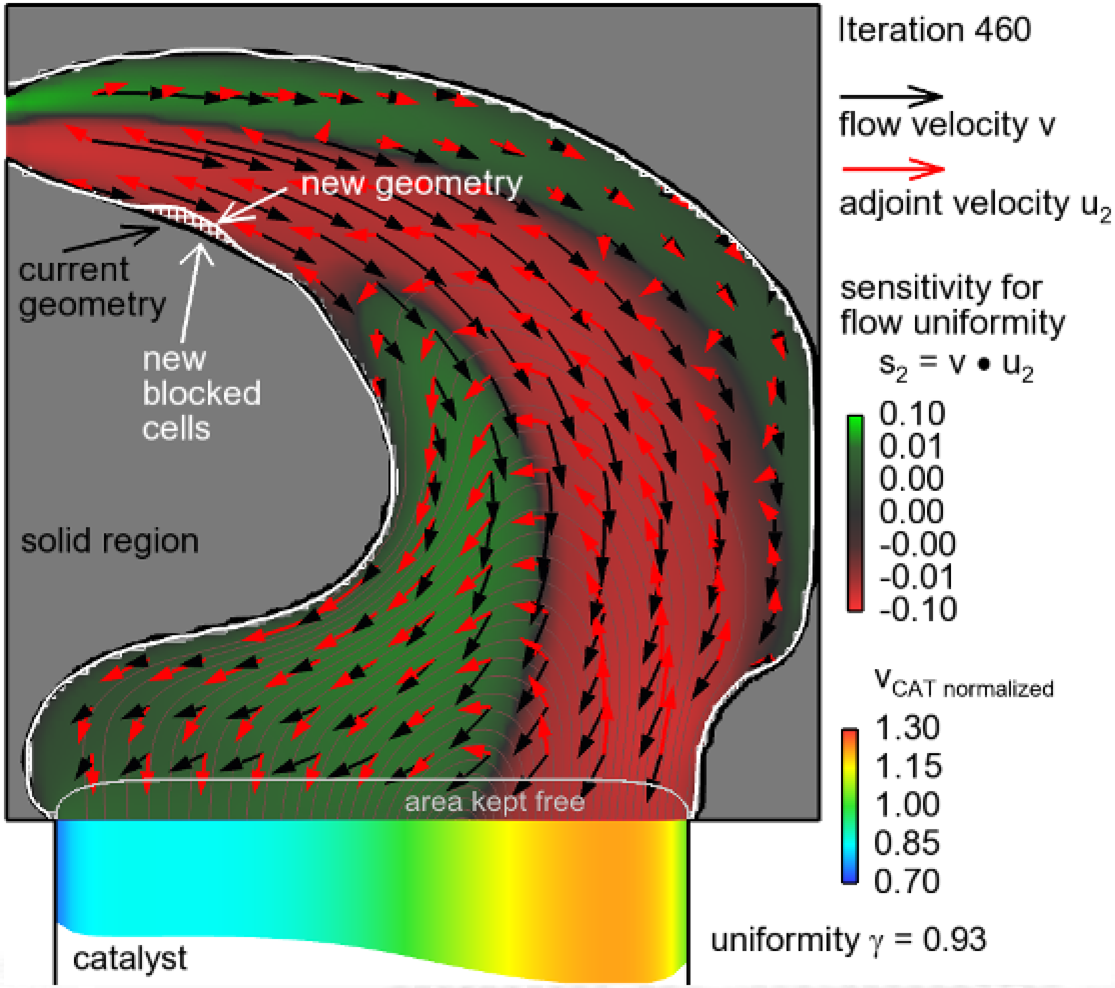
Movie

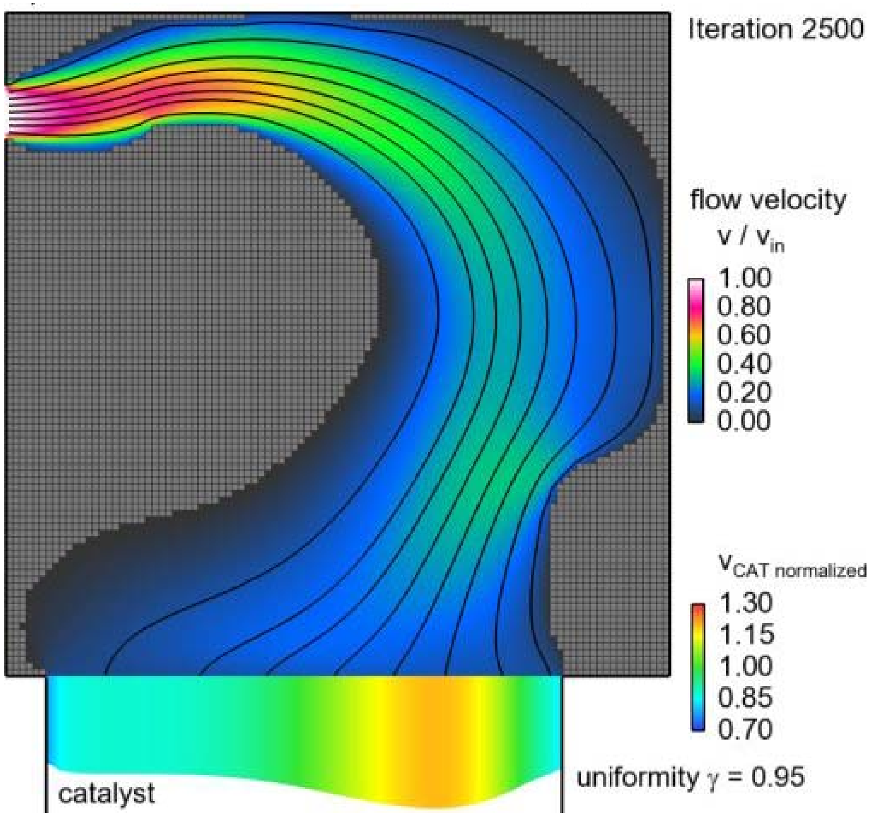
Optimisation for energy dissipation

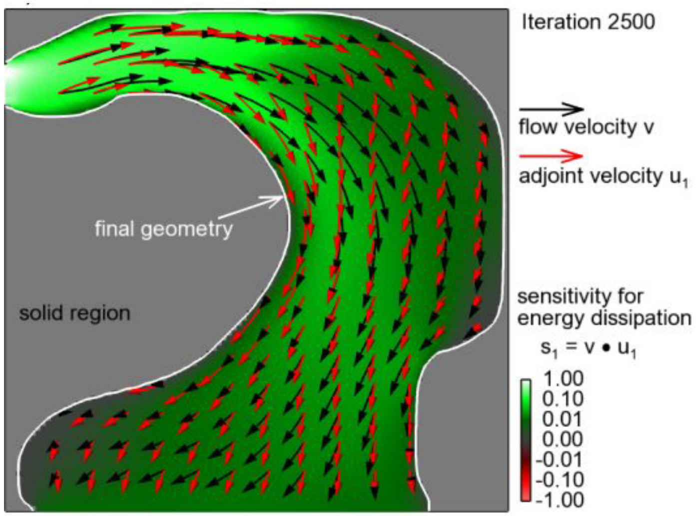


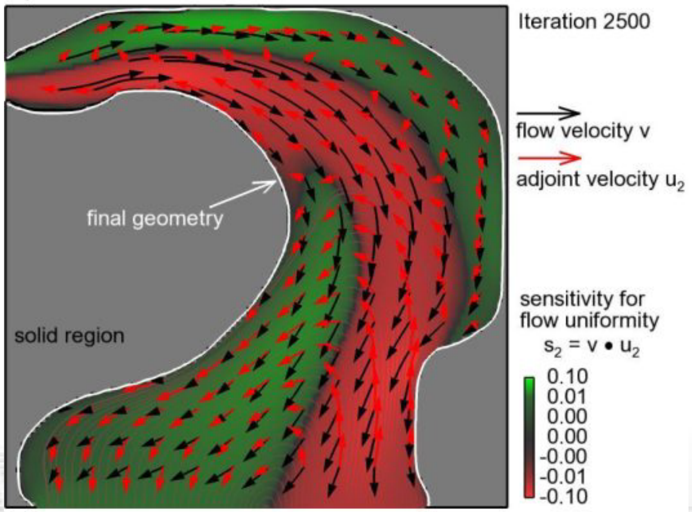
Optimisation for uniformity



Final geometry



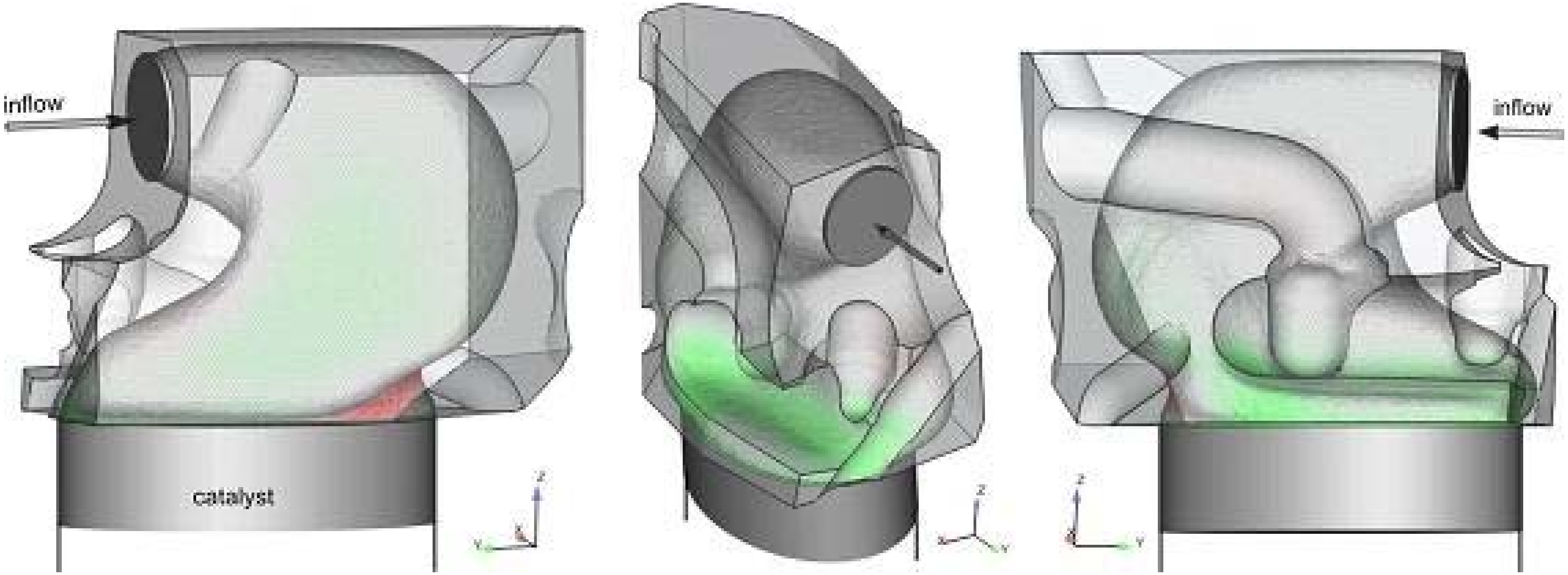




Application Examples

(pages with proprietary information have been removed)

Complex Design space

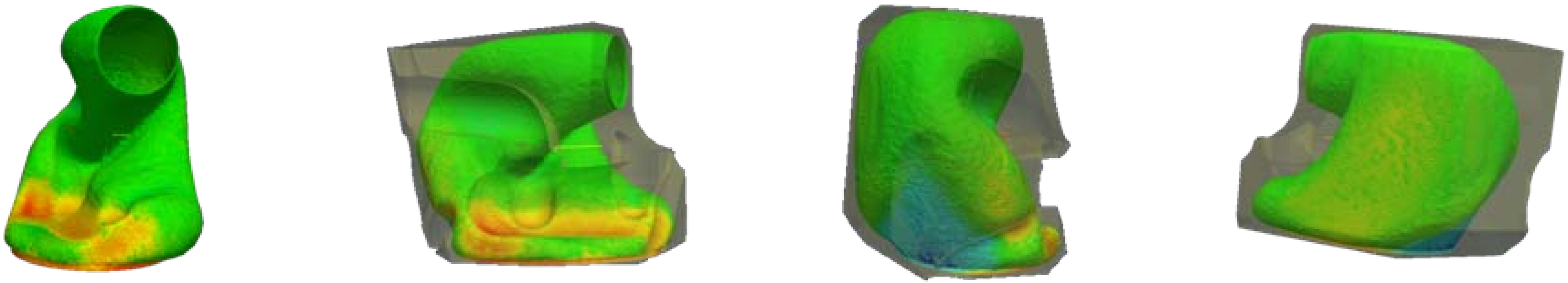


- design space meshed with 300 000 polyhedral cells
- < 10 hr simulation runtime on single CPU (3.3 GHz)
- achieved excellent uniformity $\gamma = 0.956$

Summary

CAGO (Continuous Adjoint Geometry Optimisation)

- Innovative form optimization tool
- not restricted by predefined shape functions
- robust and very fast
- helps us to find solutions for a given packaging



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