Course of Turbulence and CFD Models

Course of Computational Optimization in Fluid Dynamics

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CARMEN SANDIEGO

PIMPLES/DIMPLES ON A FLAT PLATE: A PARAMETRIC STUDY

WHY ?

- Understand the way a single pimple/dimple works
- Understand how two or more pimples/dimples interact
- Optimize their interaction and shape
- Apply pimpled / dimpled surfaces to diffusers / Ahmed body

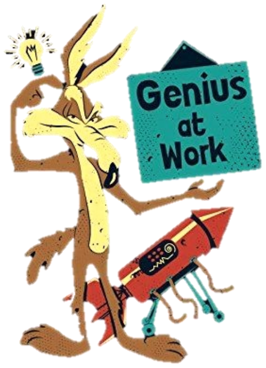
2D & 3D computations on a single device

What happens in 3D stands also in 2D?

2D & 3D computations double-device flat plate

Adjoint
3D DOE, RSM

COMPLEXITY

FLOW DATA used in the 3D setup

3D

- Re=1 000 000 → $\mu=3{,}43\cdot10^{-6}$ kg/ms, v=40 m/s, $\rho=1{,}225$ kg/m^3 , x=70mm
- Incompressible, isothermal, Newtonian, fully turbulent flow → disregard Mach, no need for Energy eqn
- Steady
- External flow: $I_t=1\%$, $\mu/\mu_T=2$

FLOW DATA used in the 2D setup

2D

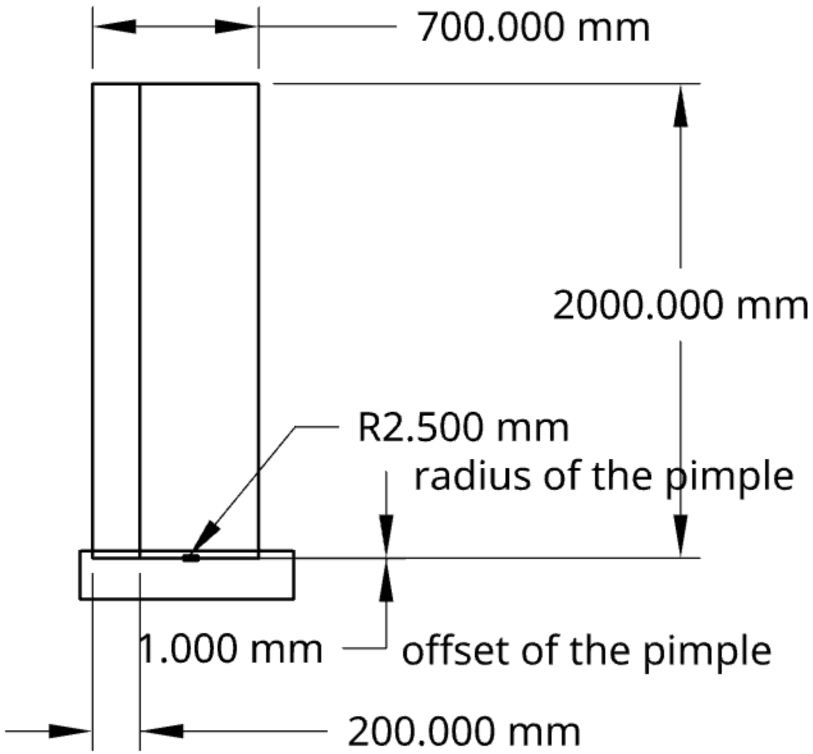
- Re=1 000 000 → $\mu=2\cdot10^{-5}$ kg/ms, v=40 m/s, ρ=1 kg/m3 , x=500mm
- Incompressible, isothermal, Newtonian, fully turbulent flow → disregard Mach, no need for Energy eqn
- Steady
- External flow: It=5% , μ/μT =10

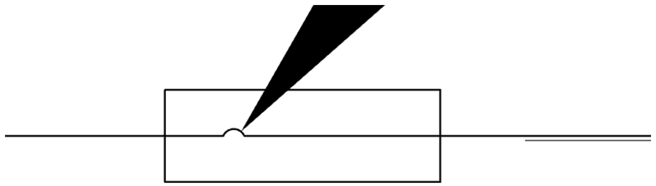
COMPUTATIONAL RESOURCES

- 1x laptop 4 cores i-7700HQ, 2.8GHz, 16 GB RAM
- 1x laptop 4 cores i-8750U, 1.8 GHz, 8GB RAM

HOW DOES A SINGLE PIMPLE/DIMPLE WORK?

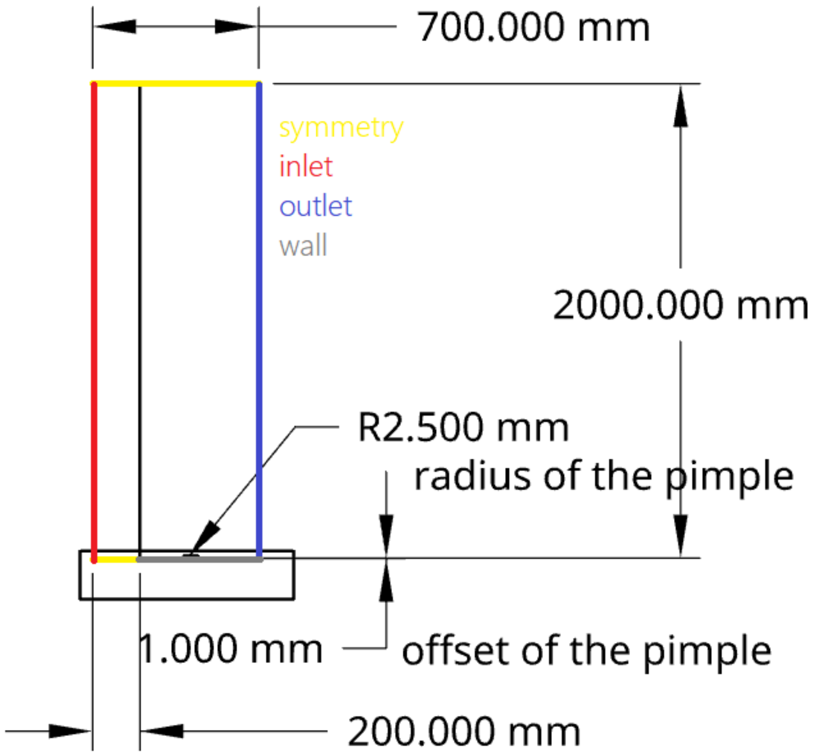
PARAMETRIC 2D STUDY:





Geometry & Mesh:

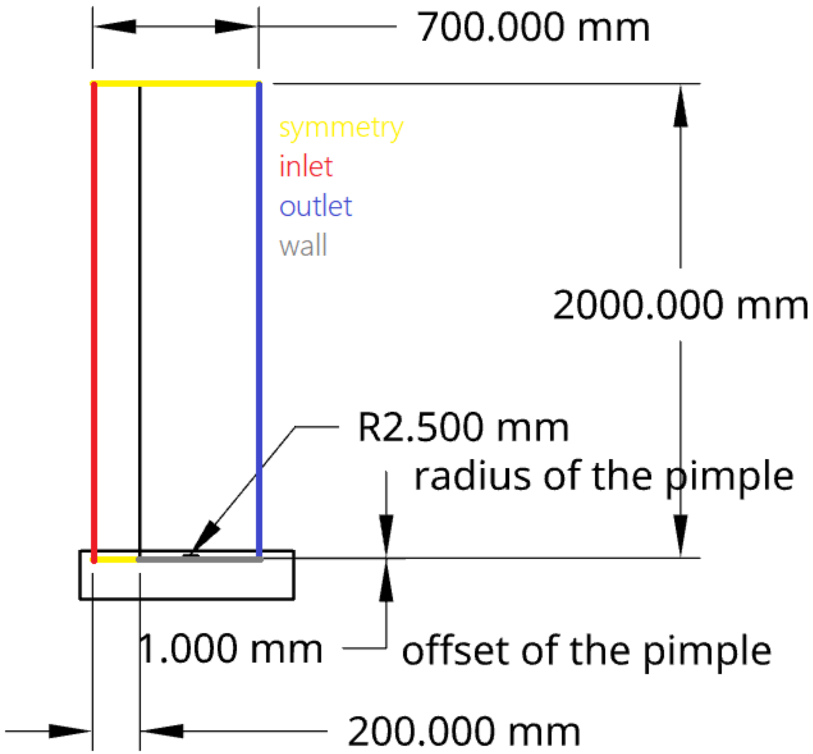
- 2 free parameters: diameter and offset;
- Channel with double body of influece, a finer one around the pimple and a coarse one all along the flat plate;
- symmetry walls right after the inlet and on the top of channel;
- First cell of the layer close to the wall to have a wall resolving approach;
- Dimple case similar to the one showed but with the device at the opposite.



2D

Mesh & Boundary Conditions

- Mesh max size: 0,05m;
- Coarse Body of influence: element size 0,002m;
- Fine Body of influence: element size 0,0008m;
- Edge sizing on the bottom sides: 0,0005m, curvature max angle 2° and local refinement set to 0,0001m to have a well resolved curvature.
- Inflation layer: smooth transition; growth rate 1,2 ; 20 layers



Setup

2D

- Double precision, pressure-based solver, steady;
- SST k-w Turbulence model, Kato Launder production limiter to account for the stagnation in front of the pimples;
- COUPLED – pseudo transient, warped-face gradients correction;
- URFs: default;
- Monitors for average and maximum y+, for Drag Force and integral of the shear stress along the plate;
- Standard initialization from inlet;

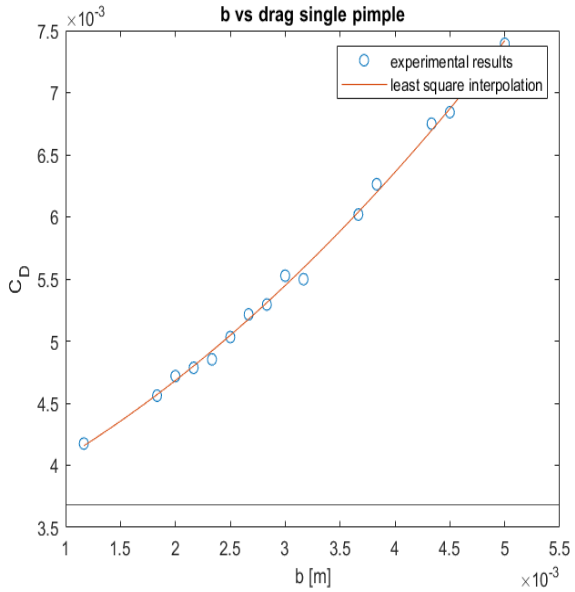
2D

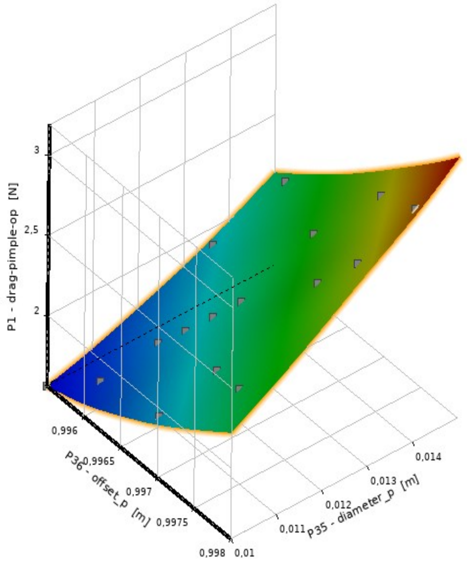
- DOE with diameter in the range 0,01 – 0,015 m and offset in 0,002 – 0,004 m;
- for the sampling it was used the latin hypercube with 15 samples and the kriging method to build the RSM;
- a correlation between the the overall height of the pimple and the drag produced by the single pimple was found in 3D and is valid also for the 2D case: it can be seen using a least square regression.

Geometries Tested in 2D

- Single pimple setup; →
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

$$drag = 73{,}6244b^2 + 0{,}3968b + 0{,}0036$$





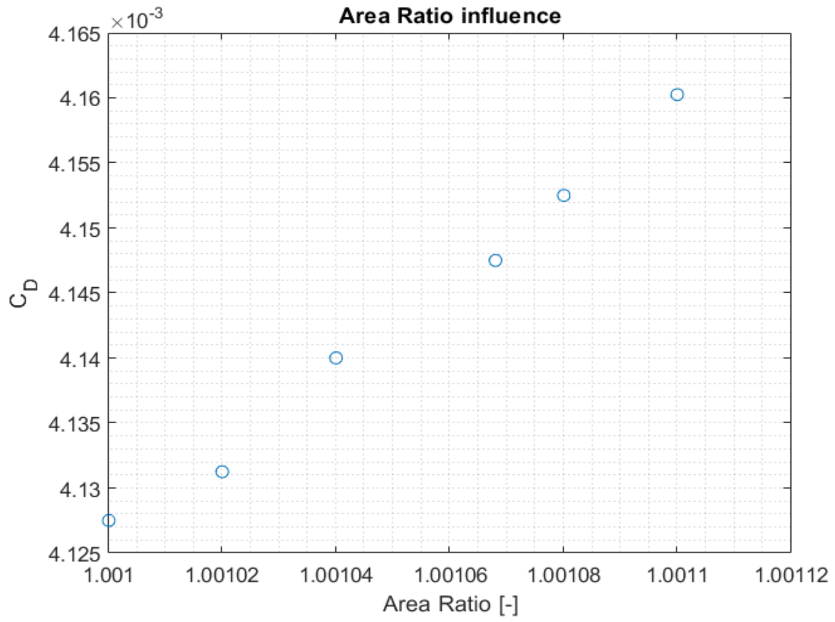
$$blockage = b = \frac{diameter}{2} - offset$$

2D

Geometries Tested in 2D

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

- A further investigation was run to find out the influence of the Area Ratio;
- The cases were run with the same blockage to isolate the effect of the Area Ratio.



- The Area Ratio has an influence on the drag produced by the pimple:

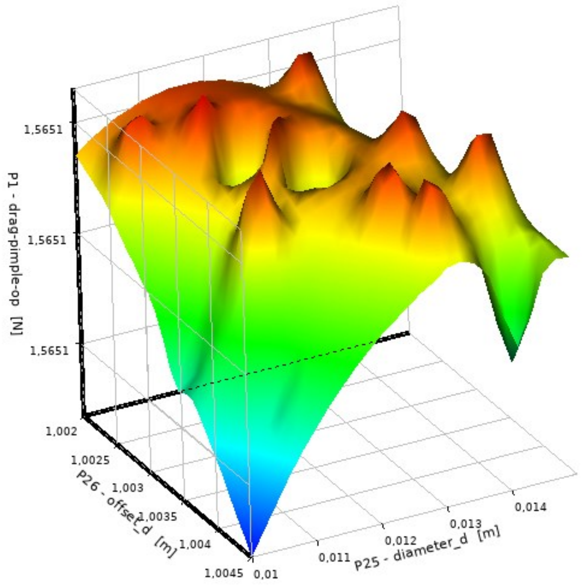
Area Ratio ↑ ⟶ **Drag Coefficient** ↑

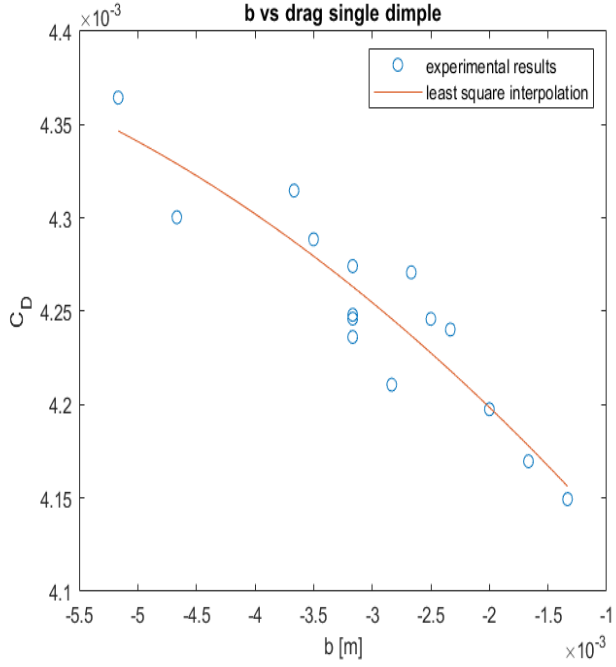
2D

- DOE with the same range as before.

Geometries Tested in 2D

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.





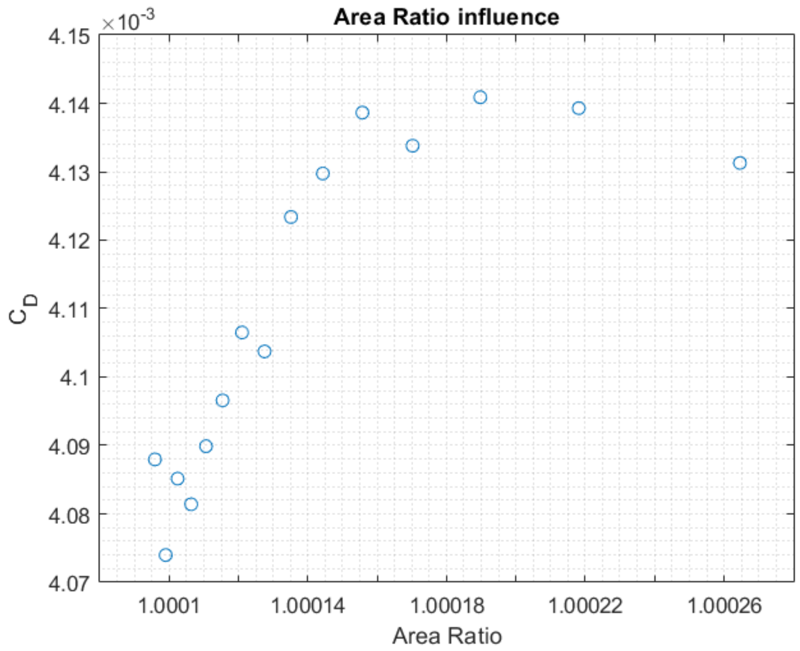
- A similar behaviour of the single pimple can be found in fact the similar the geometry is to the flat plate, the lower the drag will be.

2D

Geometries Tested in 2D

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

- Another similarity can be found in the effect of the Area Ratio on the drag:

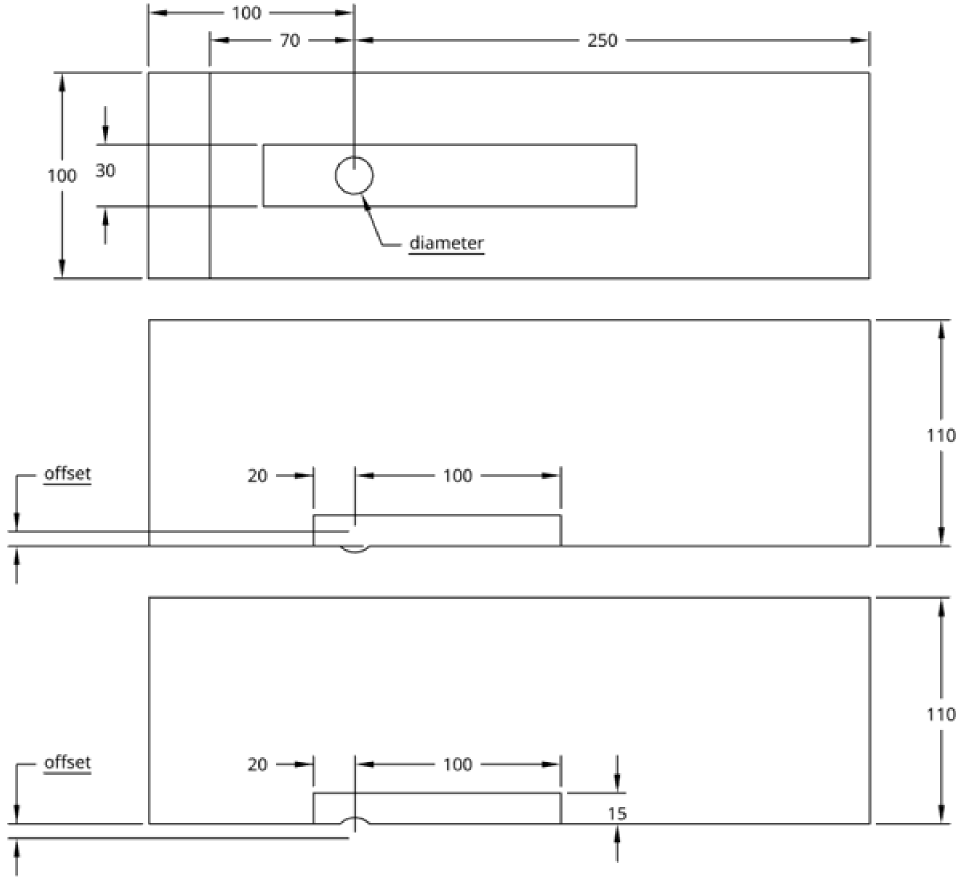


- The lowest Area Ratio implies the lowest drag also for the single dimple case.

Are there connections between 2D and 3D world?

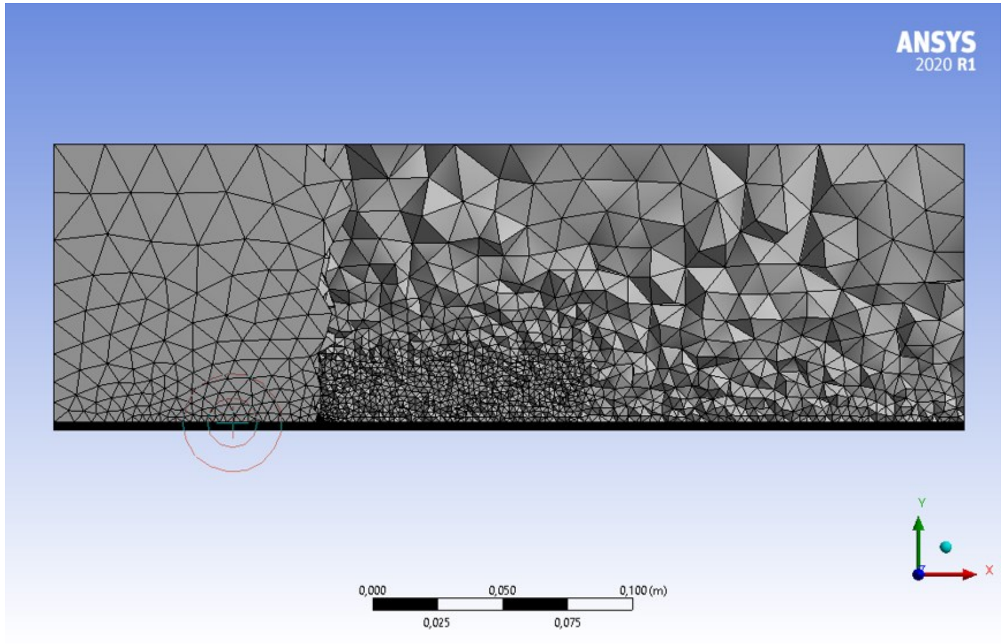
PARAMETRIC 3D STUDY:

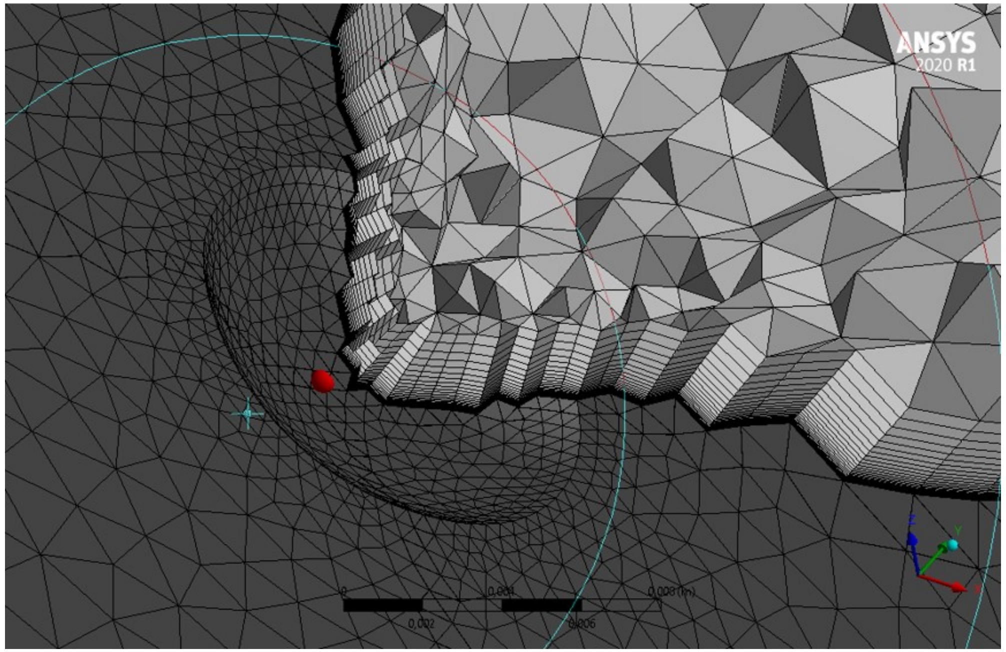
3D



Geometry:

- 2 free parameters: diameter & offset
- Simmetry walls to simulate the flat plate but gain numerical stability → pressure gradients
- Body of influence near the pimples/dimples
- Coarse mesh used only to get preliminary results
- Wall resolving approach

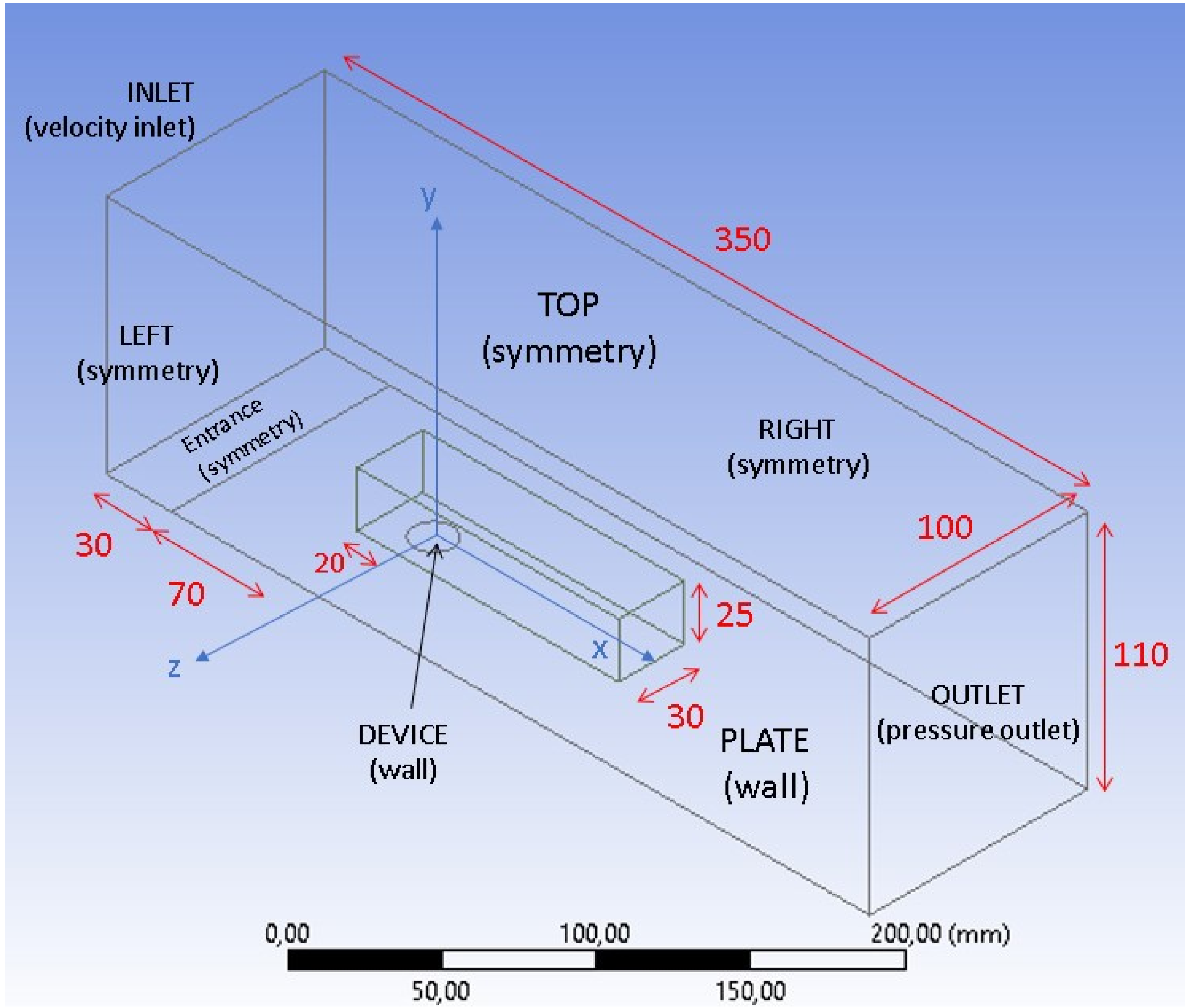




3D

Mesh (before converting to polyhedra)

- Mesh max size: 25mm
- Body of influence: element size 2.8mm
- Face sizing on the bottom sides: 2,8mm, curvature max angle 5°
- Inflation layer: first layer height 0,005mm; growth rate 1,16 ; 31 layers
- Max skewness < 0,85, Min orthogonal quality > 0,14



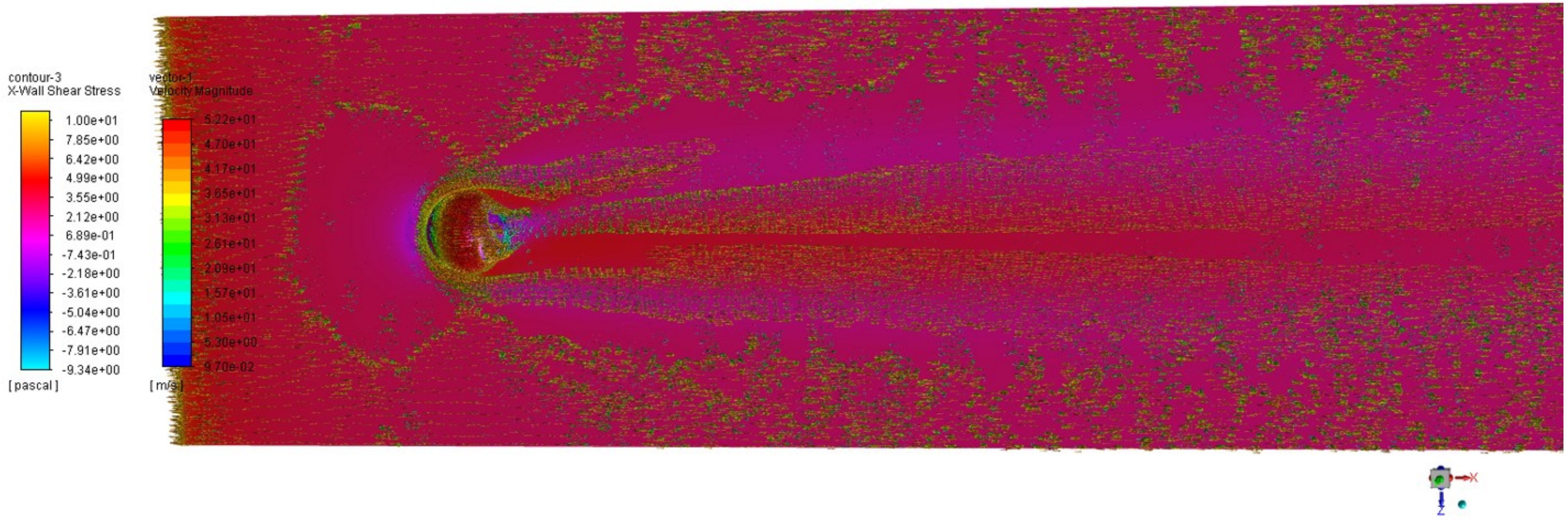
3D

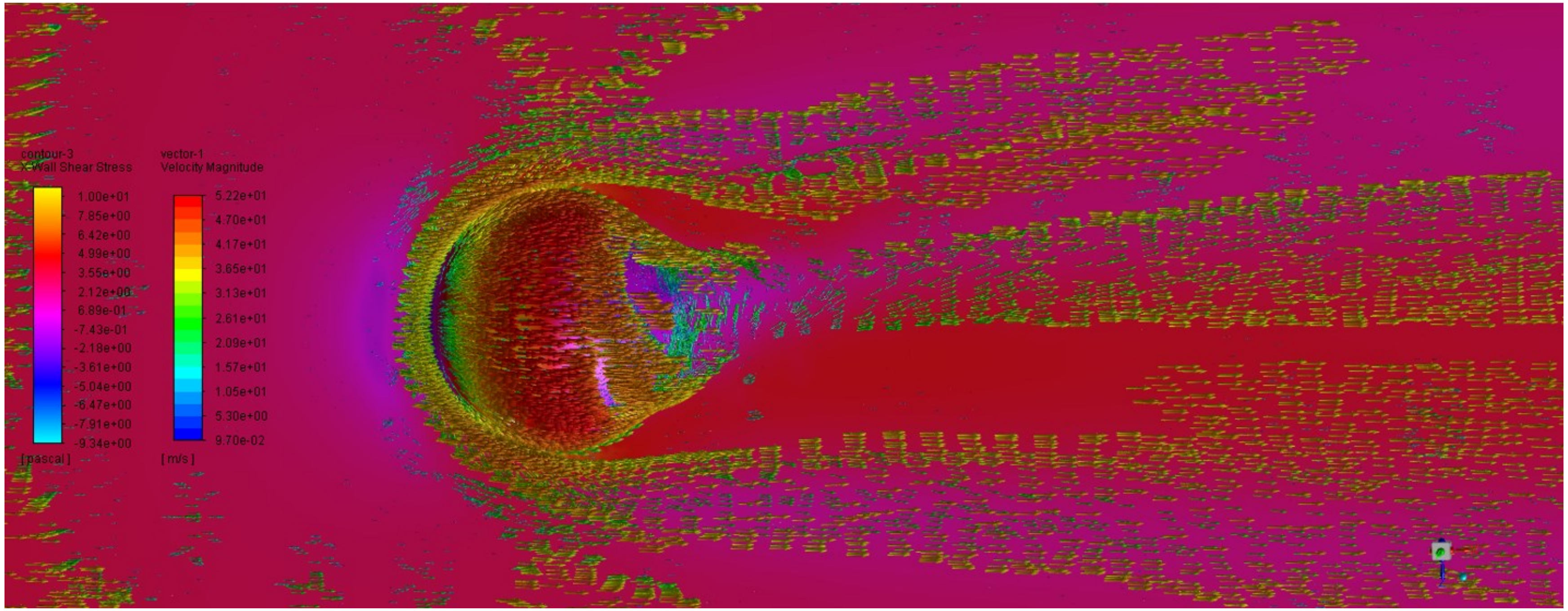
Setup

- Double precision, pressure-based solver, steady
- SST k-w Turbulence model, Curvature correction, production limiter
- COUPLED – pseudo transient, warped-face gradients correction
- URFs: default, set «1» to «0.9»
- Reports of drag and integral of X- wall shear stress, y+, mass flow
- Standard Initialization
- Run for about 160 iterations

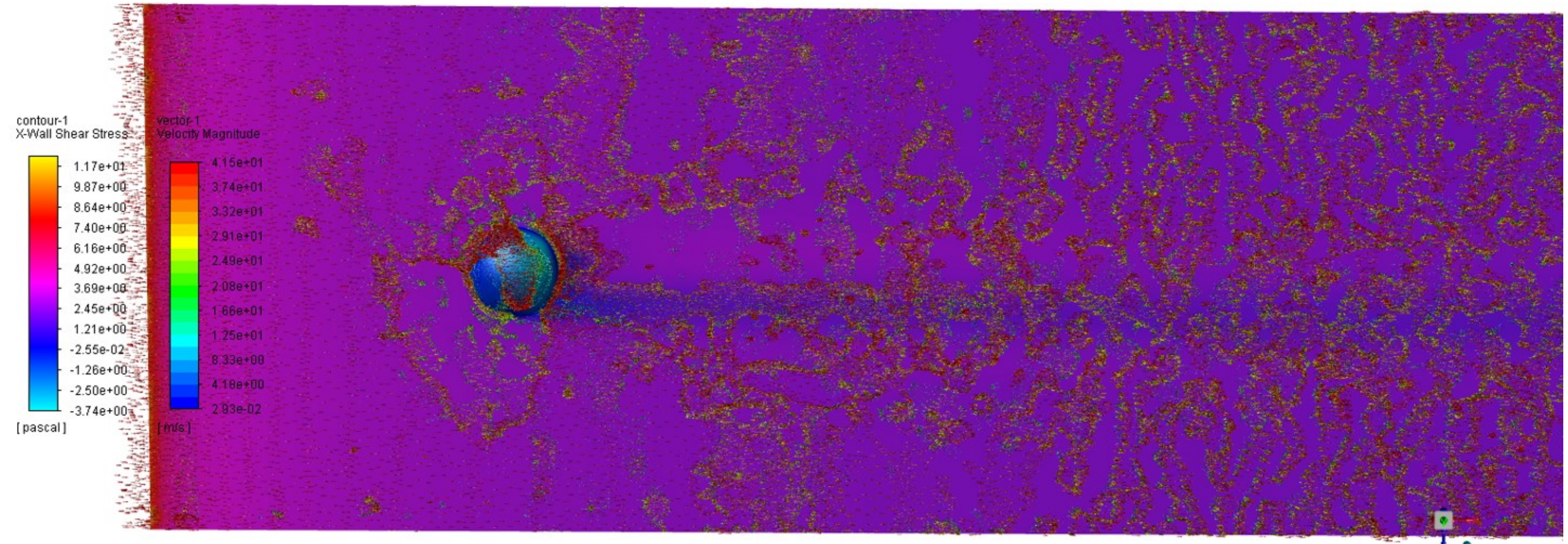
. . . RESULTS

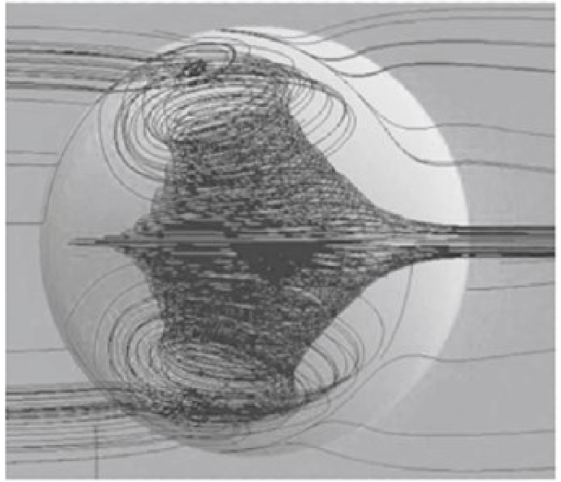
3D


contour-3
X-Wall Shear Stress
1.00e+01
7.85e+00
6.42e+00
4.99e+00
3.55e+00
2.12e+00
6.89e-01
-7.43e-01
-2.18e+00
-3.61e+00
-5.04e+00
-6.47e+00
-7.91e+00
-9.34e+00
[pascal]
vector-1
Velocity Magnitude
5.22e+01
4.70e+01
4.17e+01
3.65e+01
3.13e+01
2.61e+01
2.09e+01
1.57e+01
1.05e+01
5.30e+00
9.70e-02
[m/s]
X
Z

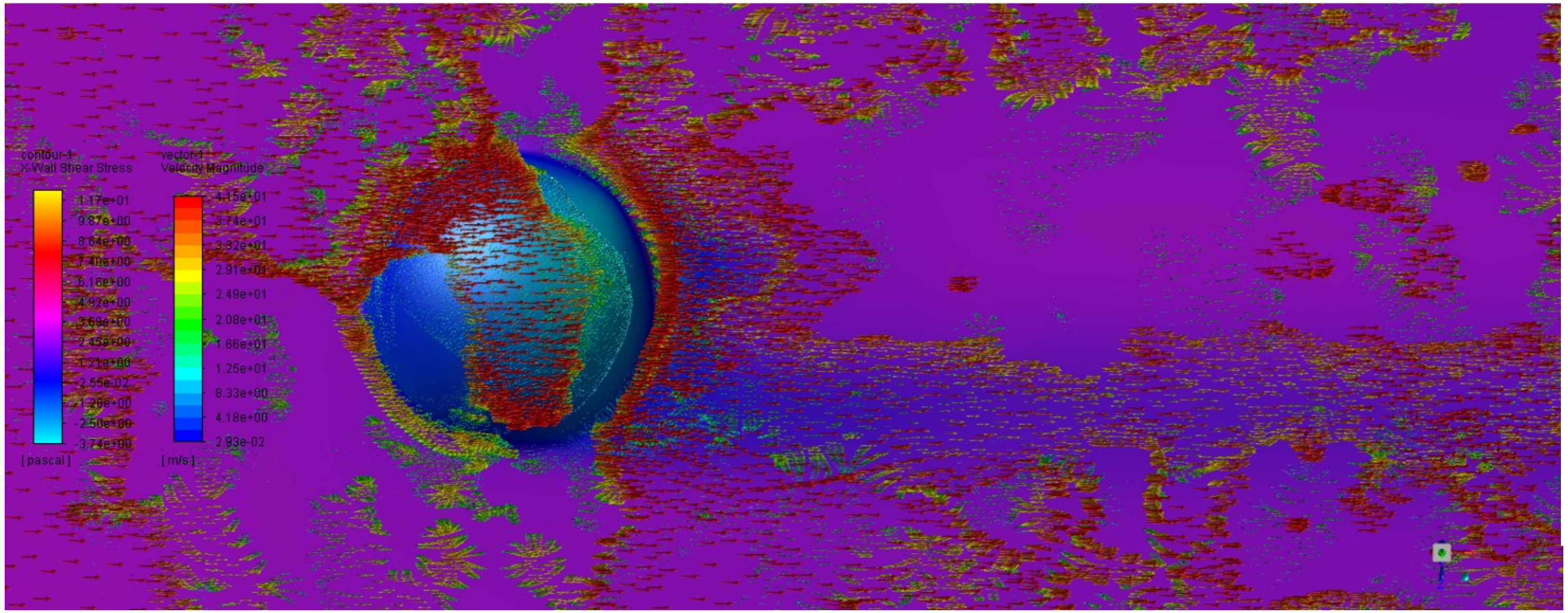

contour-3
X-Wall Shear Stress
1.00e+01
7.85e+00
6.42e+00
4.99e+00
3.55e+00
2.12e+00
6.89e-01
-7.43e-01
-2.18e+00
-3.61e+00
-5.04e+00
-6.47e+00
-7.91e+00
-9.34e+00
[pascal]
vector-1
Velocity Magnitude
5.22e+01
4.70e+01
4.17e+01
3.65e+01
3.13e+01
2.61e+01
2.09e+01
1.57e+01
1.05e+01
5.30e+00
9.70e-02
[m/s]

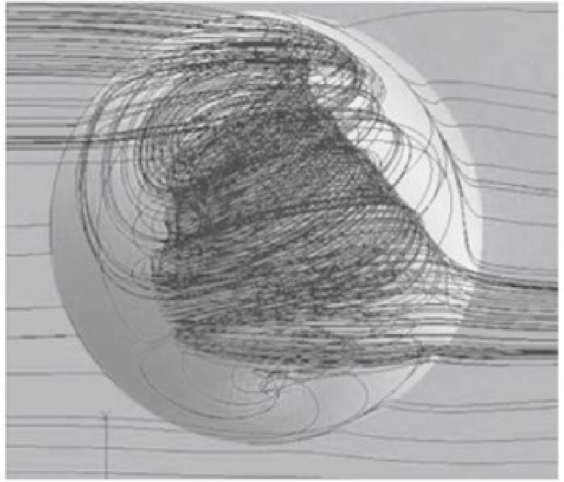
3D





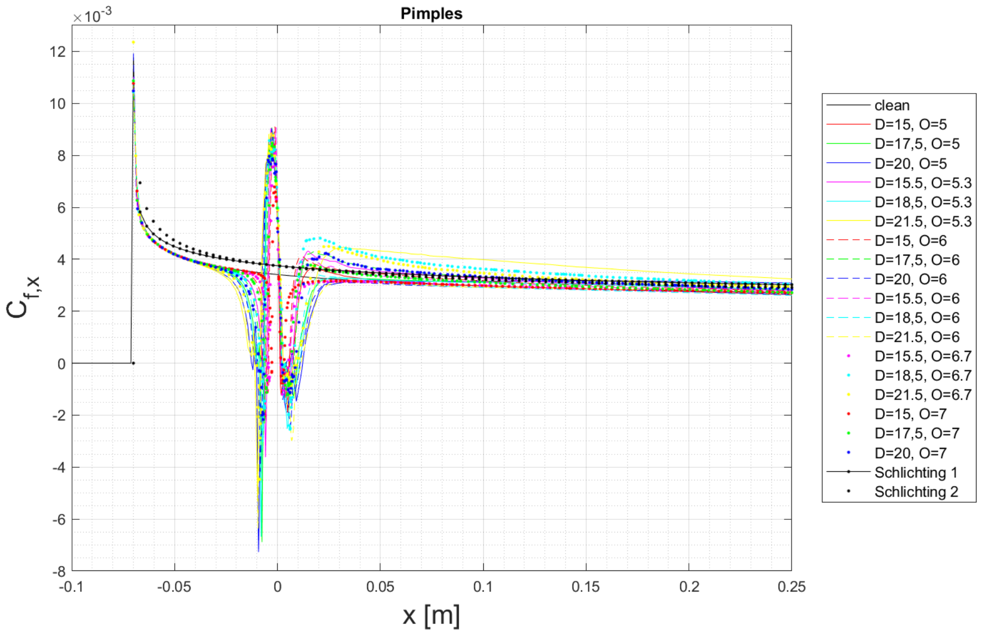
3: Counter-rotating vortex

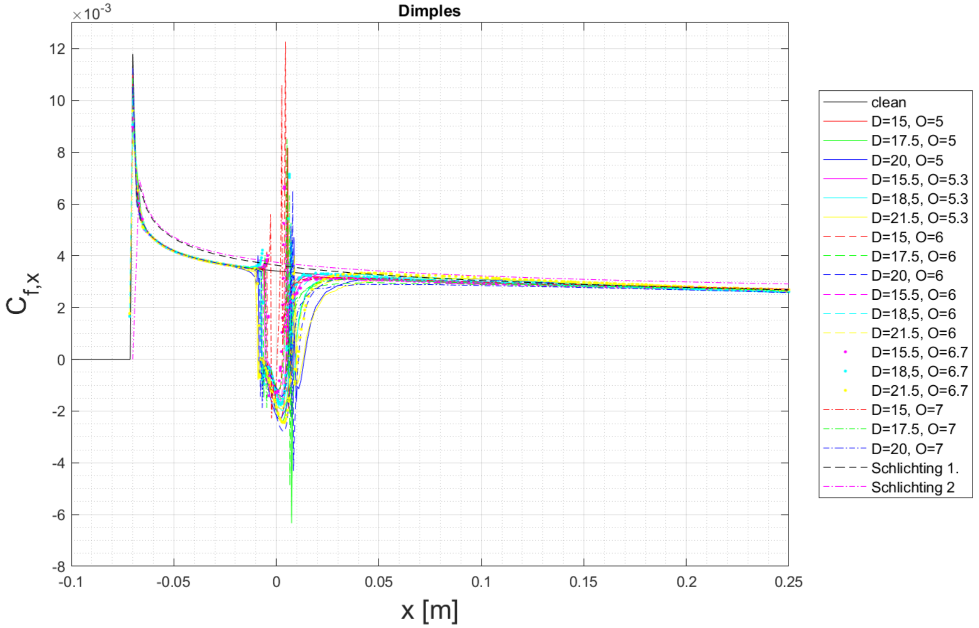




4: Tornado-like vortex (asymmetric)

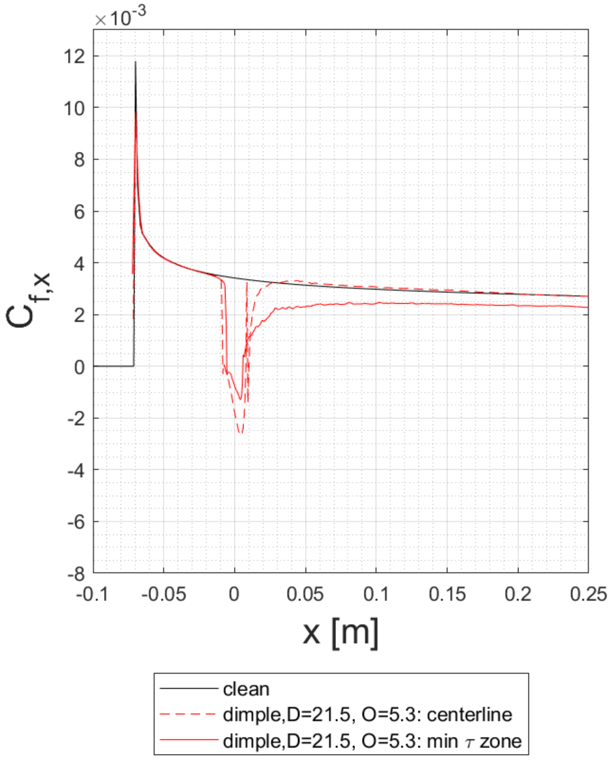
van Nesselrooij et al. 2016

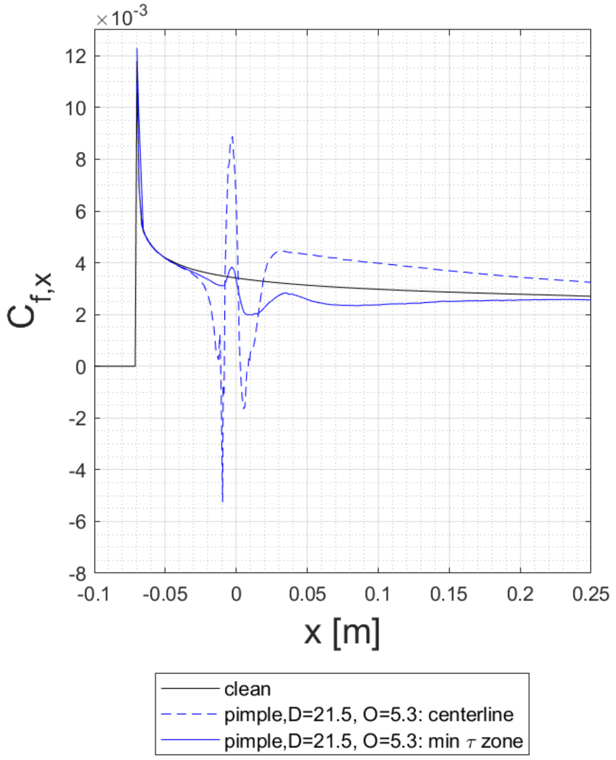




3D

- Pimple vs dimple vortex structures and wall shear zones
- Unsteadiness
- Different wall shear plots at centerline
- 2D variations for pressure and wall shear stress





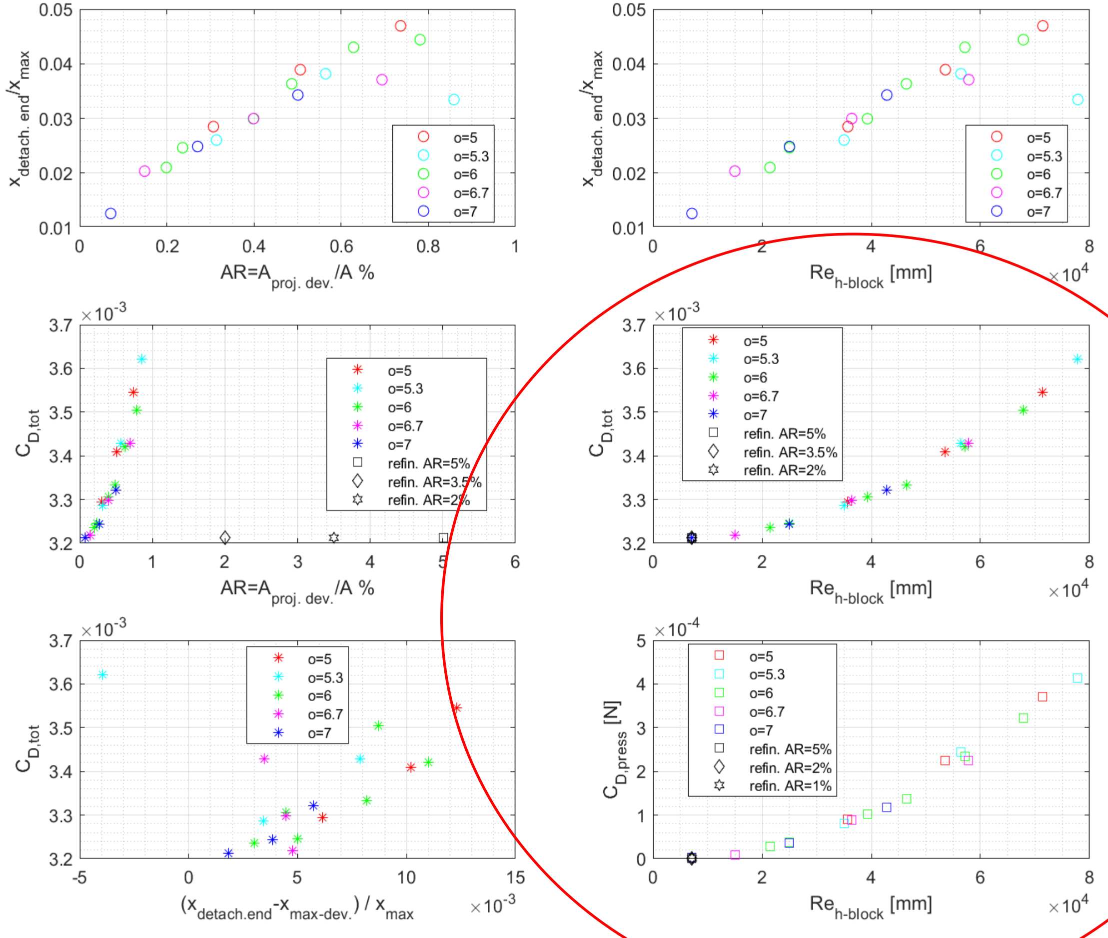
Are there key parameters?

3D

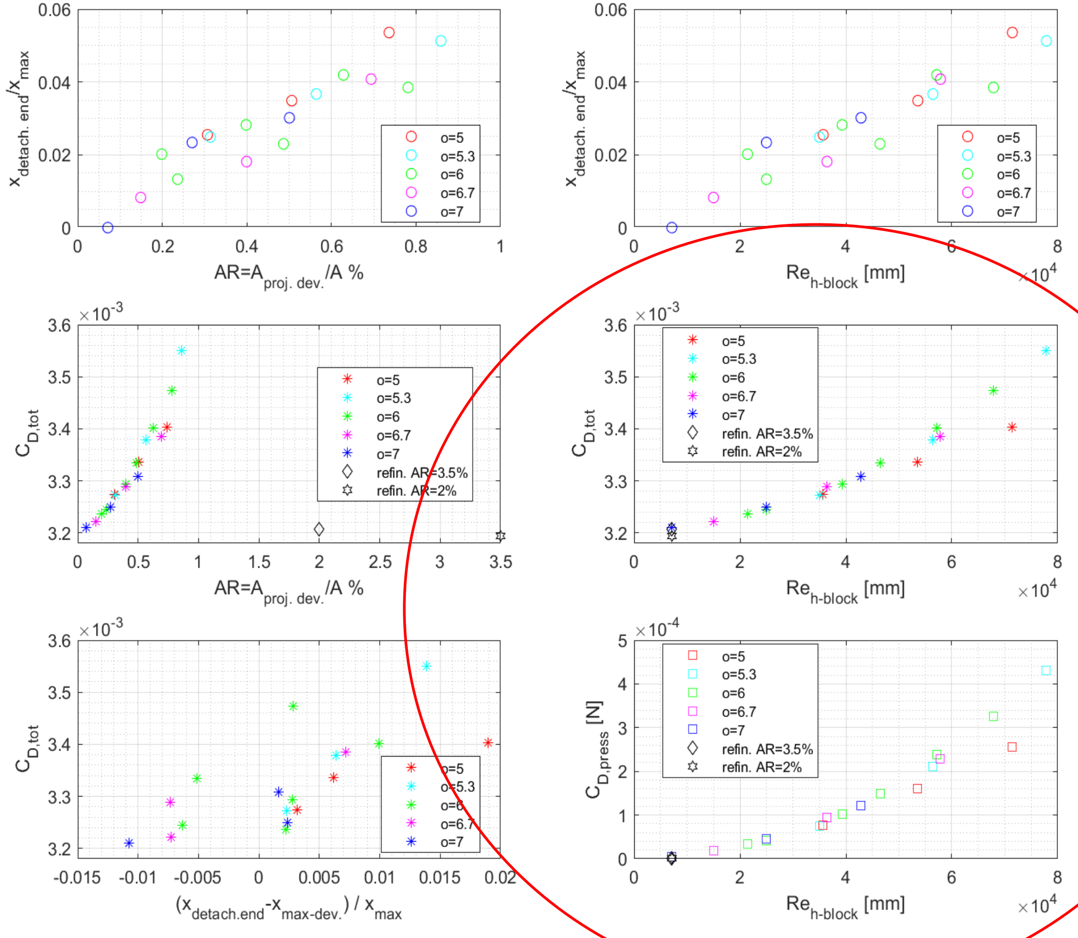
$$Re_{h-block} = \frac{\rho v h_{block}}{\mu} \qquad h_{block} = diameter/2 - offset$$

$$AR = area-ratio = \frac{A_{projected,device}}{A_{flat-plate}} \qquad C_{D,i} = \frac{D_i}{0.5\rho v^2 S}$$

Pimple

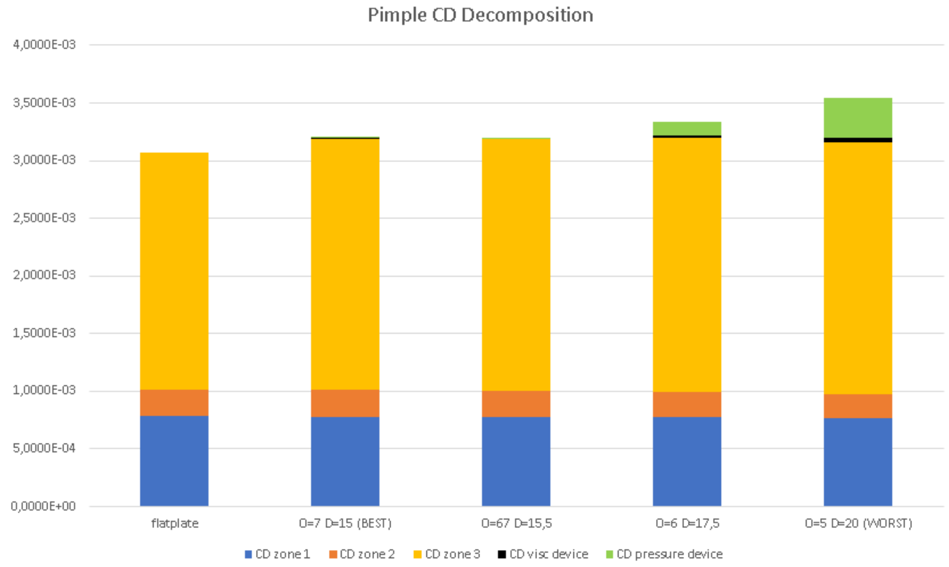


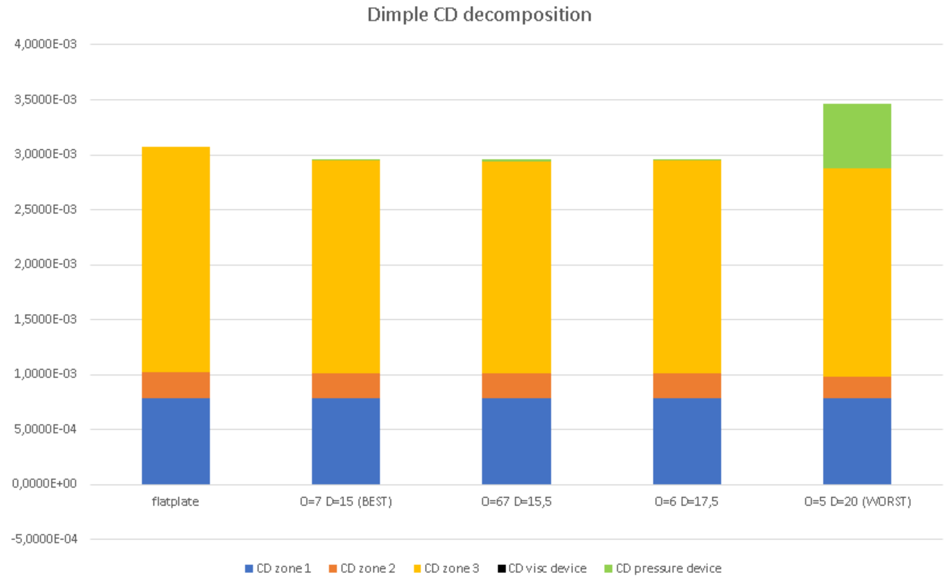
Dimple

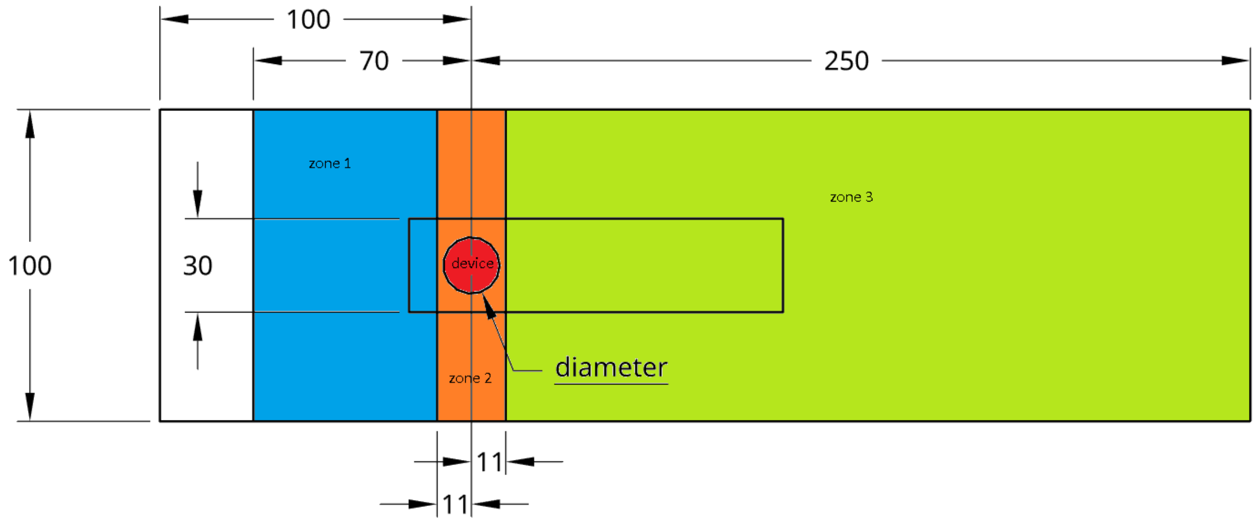


Where do we find the main variations?

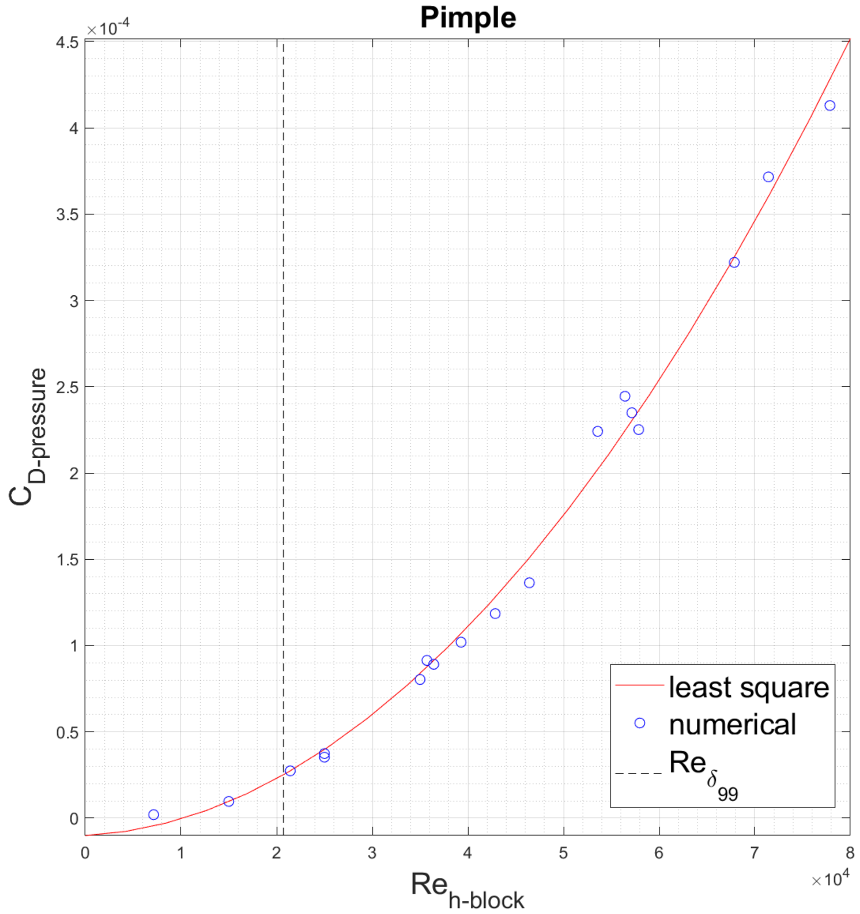
3D

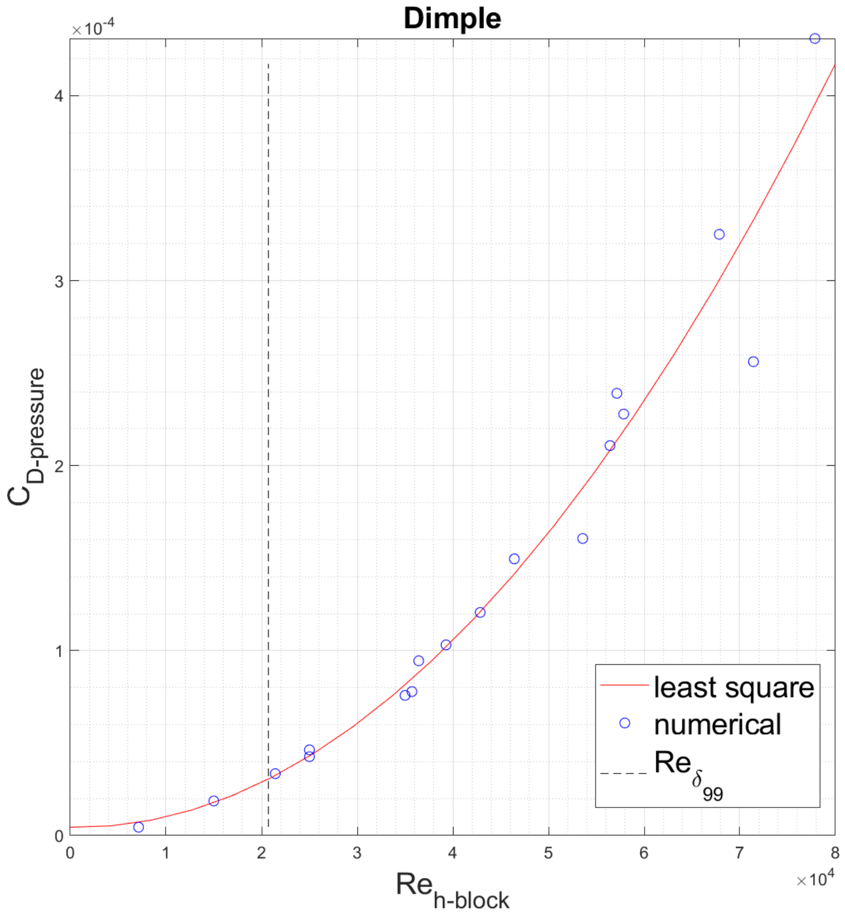


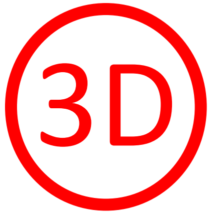




- Geometry changes mainly affect pressure drag
- In pimples viscous drag is always positive, in dimples may become negative
- The key parameter is the blockage height and it affects pressure drag







$$C_{D,p-pimple} = -1.0097 \cdot 10^{-5} + 2.7481 \cdot 10^{-10} Re_{h-block} + 6.8733 \cdot 10^{-14} Re_{h-block}^2$$
$$C_{D,p-dimple} = 4.5005 \cdot 10^{-6} - 1.0591 \cdot 10^{-10} Re_{h-block} + 6.5812 \cdot 10^{-14} Re_{h-block}^2$$

We will take as optimal the design offset=7mm, diameter=15mm (Re_{hblock}=7143)

HOW DOES A COUPLE OF DEVICES INTERACT?

BACK TO 2D

Geometries Tested in 2D

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

So far it was tested the single device behaviour, both for the pimple and the dimple case.

As it was done before, a 2D analysis can give some preliminary indications on what geometry can be useful to elaborate on, and to analyze in 3D.

This further step ahead was needed to:

- have a better comprehension of the interactions between the pimples and the dimples;
- understand if the same behaviours found before, were also valid if there were interactions.

2D

Geometries Tested in 2D

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

Constrains used for the setup of the double pimple case:

- The blockage height to coincide with the best one found for the pimple;
- The minimum spacing to to avoid the merging of the pimples and the interaction between the recirculation area.

Influence of the Area Ratio with equal overall heigth of the pimple:

Diameter[m]	Min spacing [m]	Max spacing [m]	Best C_D	Best spacing
0,1	0,022	0,3	0,00408	0,036
0,05	0,015	0,3	0,0041	0,047
0,01	0,007	0,3	0,0042	0,03

- The best was found in the case of the highest Area Ratio;
- It was found that the spacing didn't have an high influence until a spacing of 0,2m was reached, then the drag started growing.

2D

Geometries Tested in 2D

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

Constrains used for the setup of the double dimple case equal to the double pimple case.

Following what was found before, the DOE was made using the best results found in the single dimple case, allowing only the spacing to change.

2D

Geometries Tested in 2D

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup; →
- Dimple Pimple setup. →

Constrains:
- Low Area Ratio;
- Low spacing (below the 0,2 m limit found before).

- No influence of the spacing found, and same results for the two geometries.

2D

Best Results ?

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

The best configuration among the tested is the single pimple one, with the following geometrical parameters:

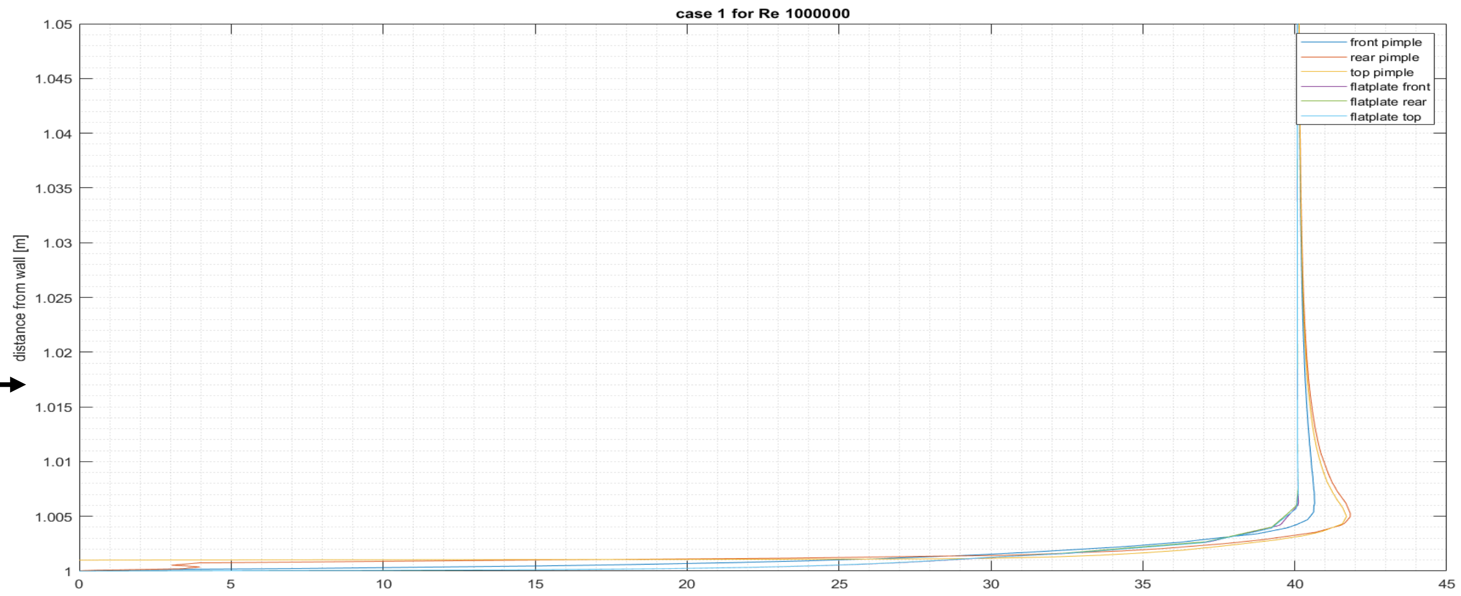
- Blockage 0,001m;
- Area Ratio 1,00026;

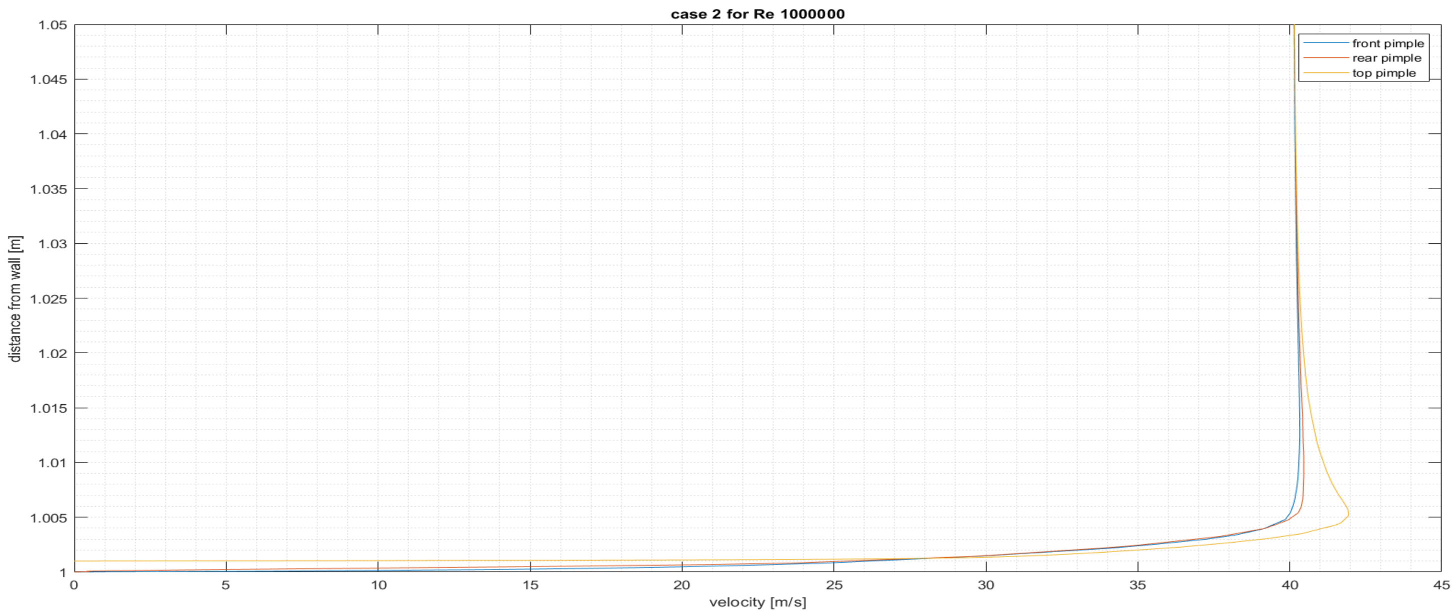
This configuration allowed to find $C_D = 0{,}004071$ that is the closest to the flat plate ($C_D = 0{,}0039$) among the tested geometries.

- It can be analyzed the velocity profiles close to the pimple of the best configuration and make a comparison with another case.

Best Results ?

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.





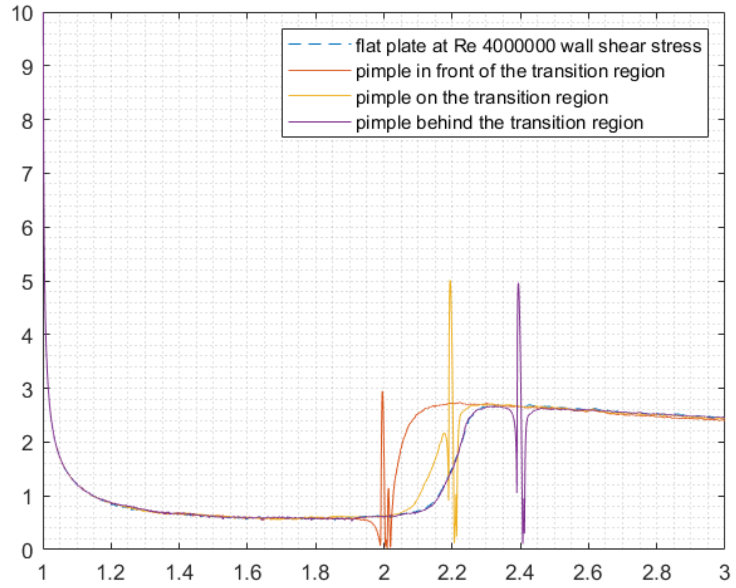
2D

Best Results ?

- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

- In the first plot, on the rear velocity profile, it can be seen a small region with where there’s recirculation, while in the second plot that region is smaller.

- For the best case it was run a further simulation with the transitional SST model to find out the influence of the pimple in the transition process.



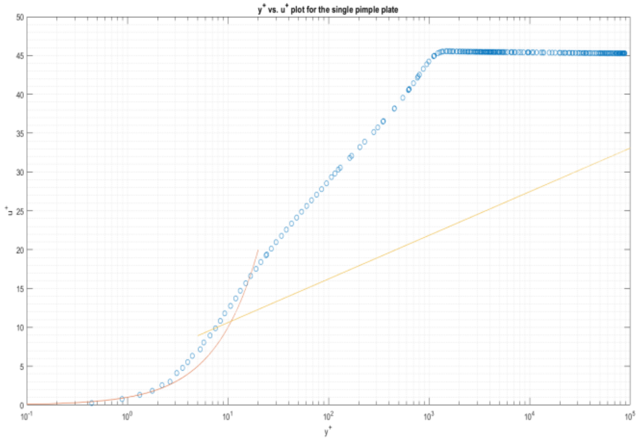
- As it could be predicted the best positioning of the pimple is behind the transition point, because if put before it triggers the transition.

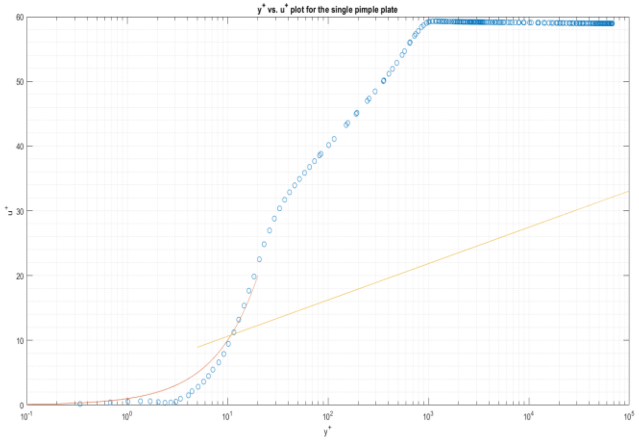
2D

Best Results ?

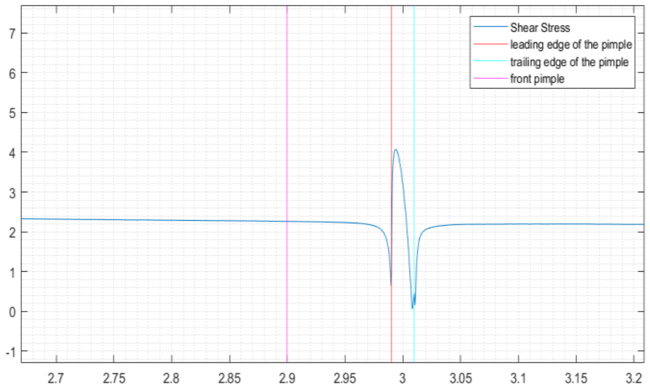
- Single pimple setup;
- Single dimple setup;
- Double pimple setup;
- Double dimple setup;
- Pimple Dimple setup;
- Dimple Pimple setup.

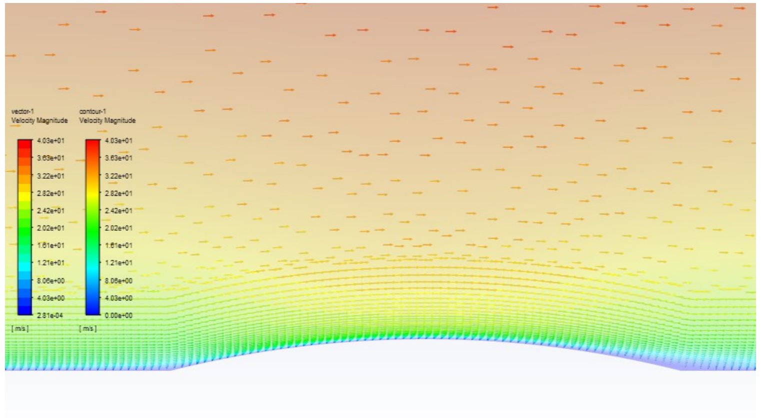
- Non dimensional velocity profiles on the leading and trailing edge were plotted;





- Right before and after the pimple the flow follows for a short section the viscous sublayer law, and this implies lower viscous drag:





Are there connections between 2D and 3D world?

3D

Problems

- Much heavier computations
- We need to resolve well in the wake (min R_L=3)
- We can afford no more than 3 MLN- cell meshes
- Only one computer can afford these computations
- One DOE is at least 4x4 computations

New features

- New poly-hexa mesh (Fluent Meshing)
- Periodic BCs
- 2 full- length BOIs, one fixed and one moving

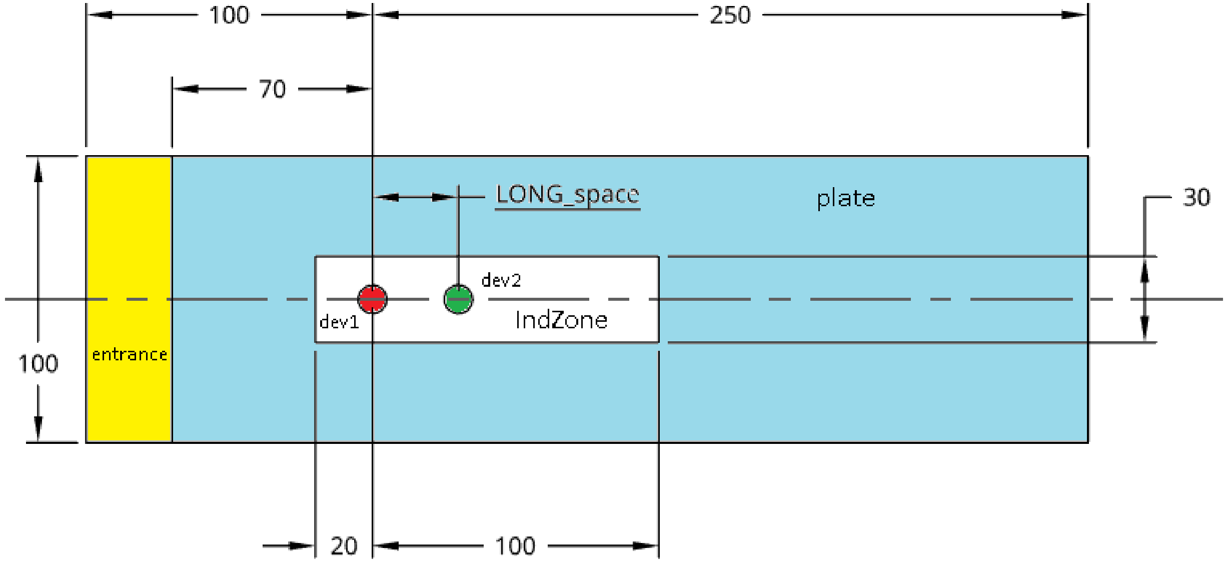
Simulations can no more be updated using Ansys WB loop, DOE, RSM

Assumptions

- Optimal blockage height 0,5mm (Re_{hblock}=7143)
- Pimples may help on diffusers because they change the slant angle and generate strong vortices
- Preliminary computations with a coarser mesh suggest that PP is the most efficient configuration

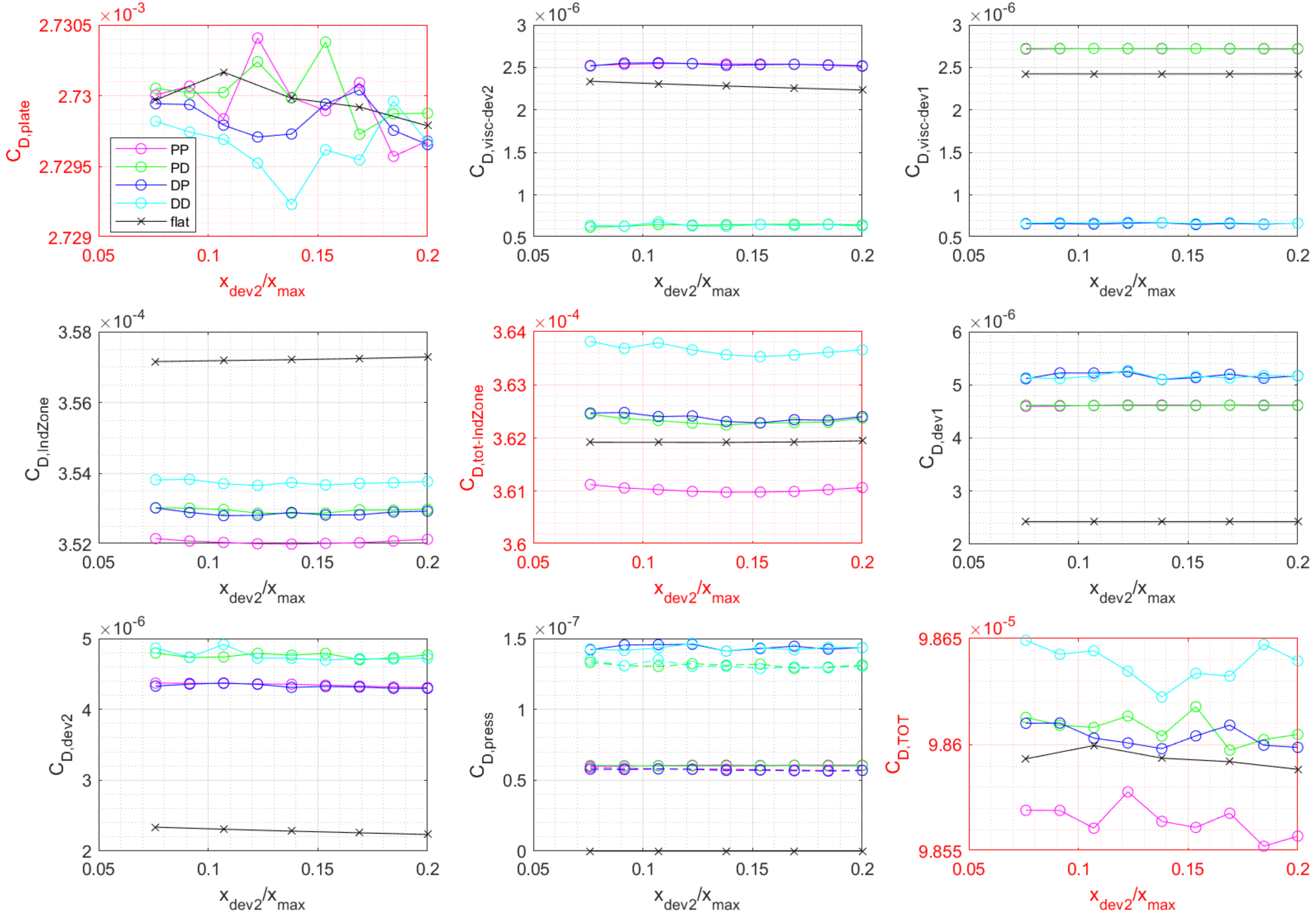
Preliminary computations

3D



- Mesh max size: 25mm
- BOI: 0,8mm, growth rate 1,1
- Face sizing plate: 3,5mm, soft, growth rate 1,1
- Face sizing IndZone and devices: 0,8mm, growth rate 1,1, curvature 5°
- Inflation layers on all bottom walls: first layer height 0,0025mm, 35 layers, growth 1,14

3D

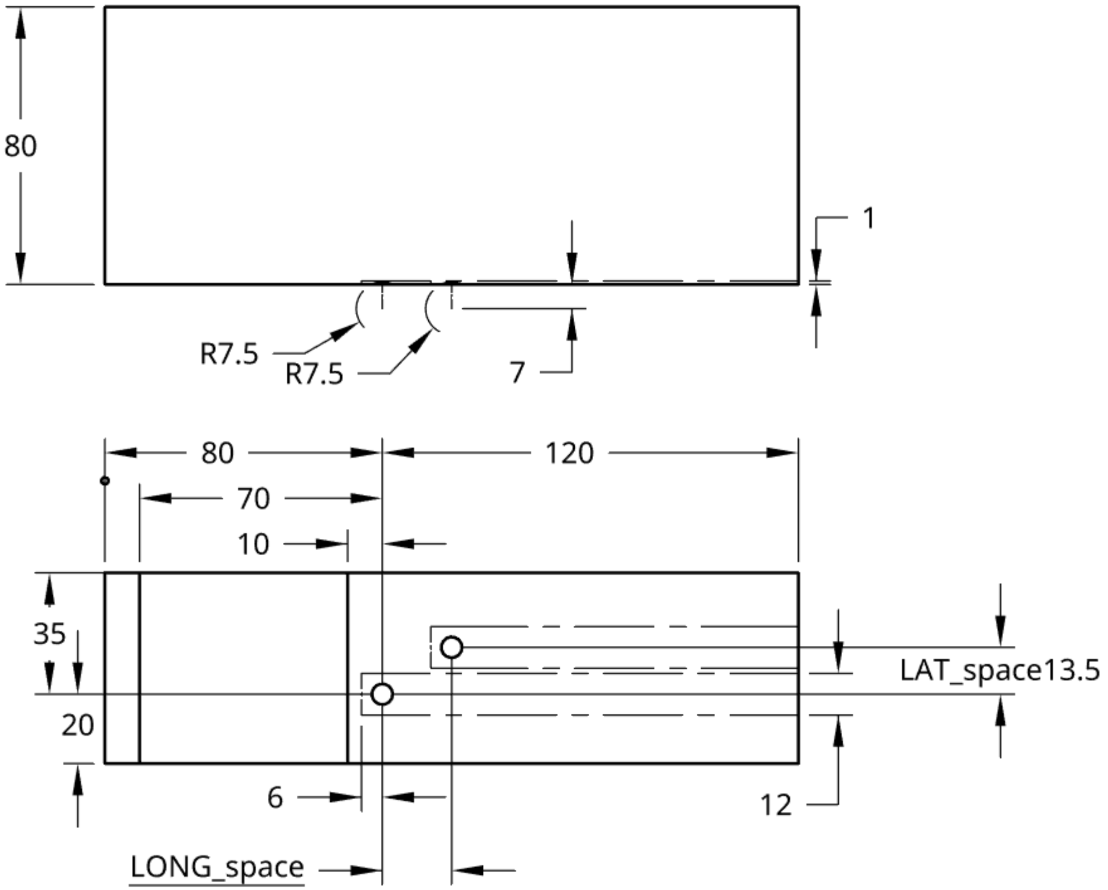


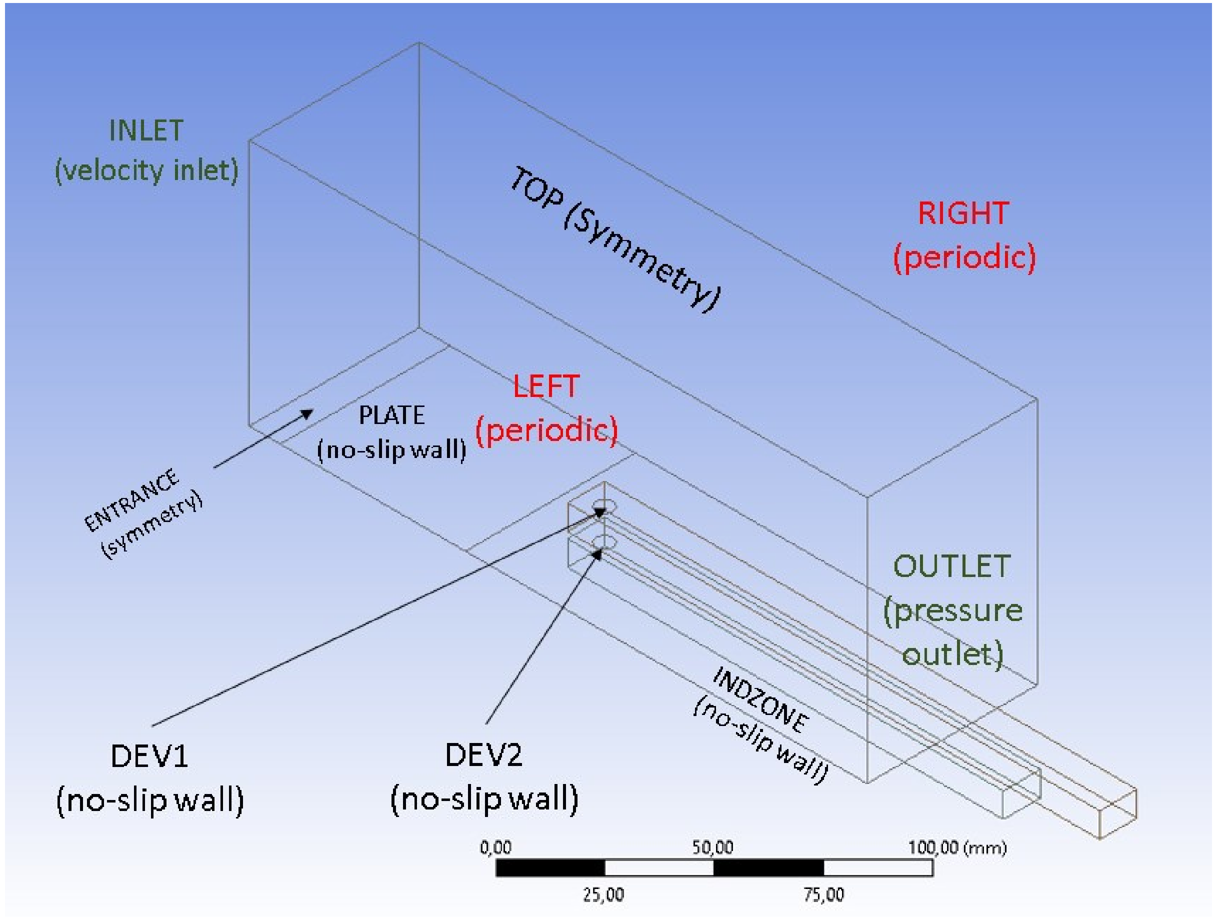
- There is mesh- noise
- The most promising case is PP
- Maybe PP could be also better that the flat plate (?)

Examine PP first

Pimple-Pimple case

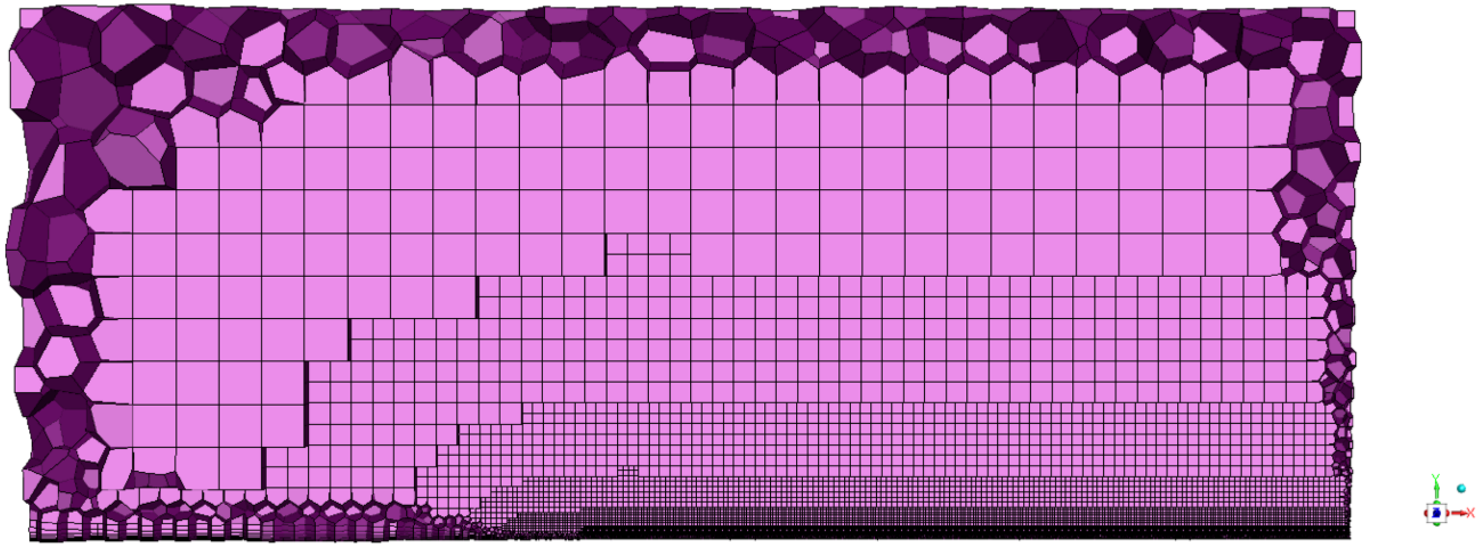
3D

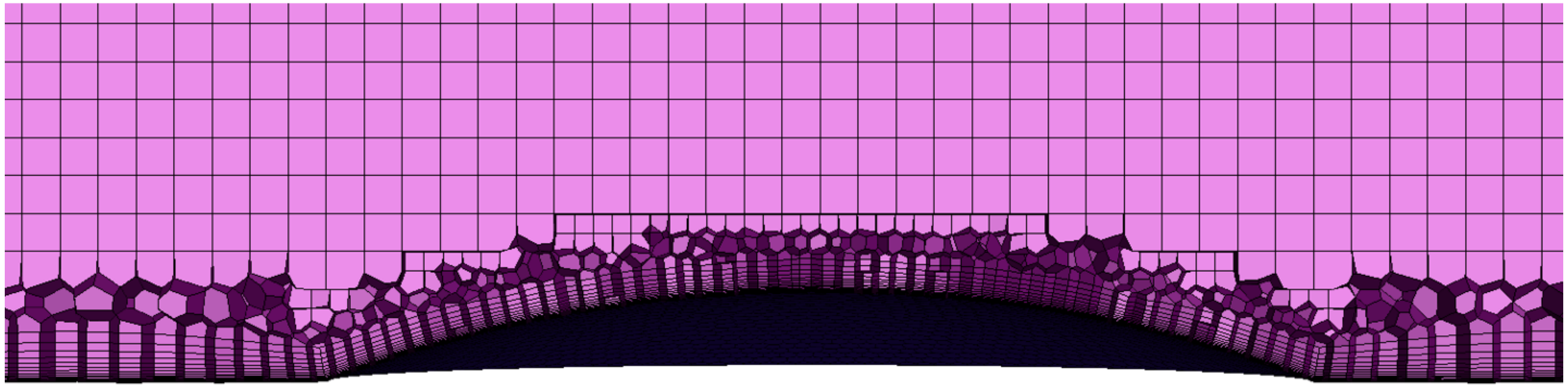




Mesh (Fluent Meshing)

3D

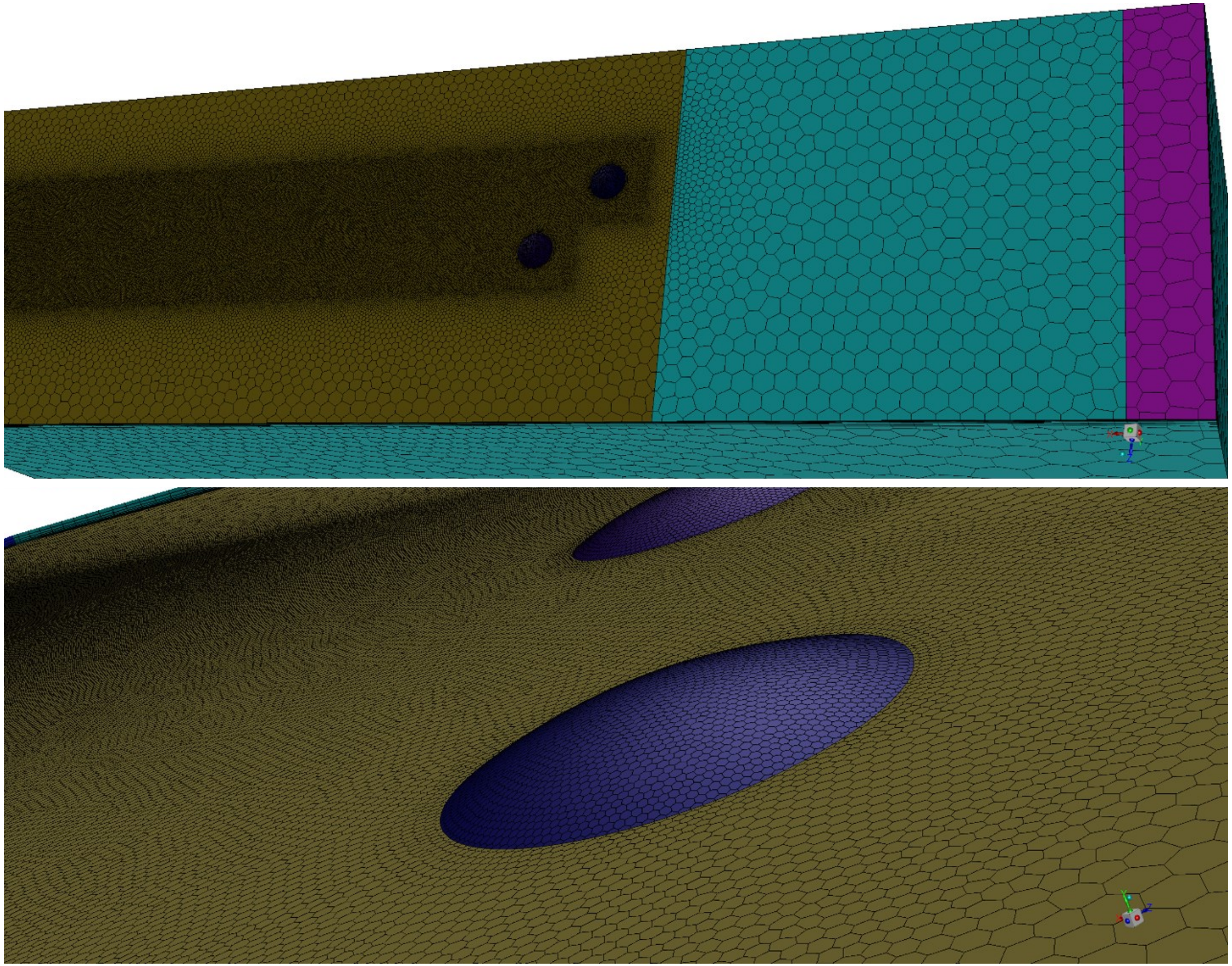




Mesh settings:

- Workflow: watertight geom.
- Mesh max size: 20mm
- BOIs: target size 0,2mm; growth rate 1,15;
- Curvature on *dev1*, *dev2*: local min size 0,1mm, max 0,12mm; normal angle 3°, growth rate 1.11
- Face sizing on *IndZone*: target size 2.8mm, growth rate 1.12
- Face sizing on *plate*: target size 3mm, growth rate 1, 2
- Face sizing on *left, right, top, inlet, outlet*: target size 20mm, growth rate 1,2
- Prism layers on bottom walls: «last-ratio», last layer height 0,0023mm, 15 layers, default ratio.

3D

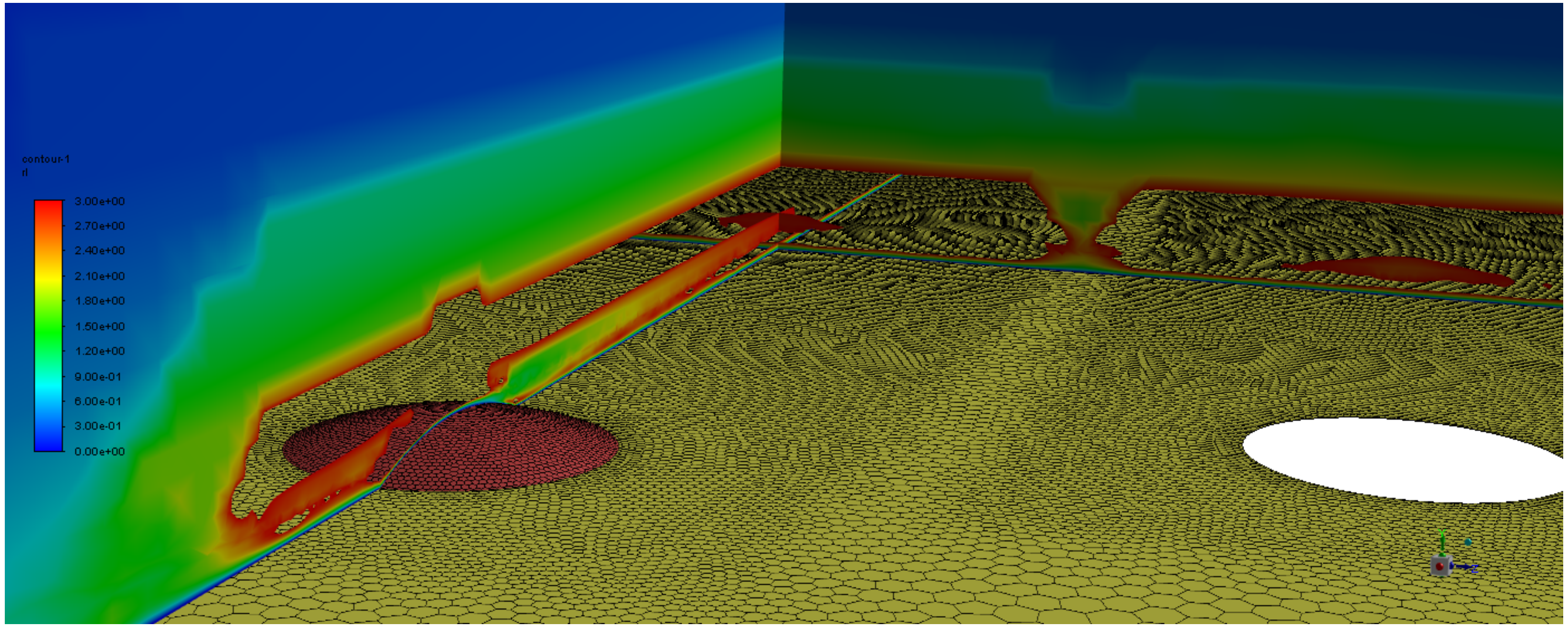


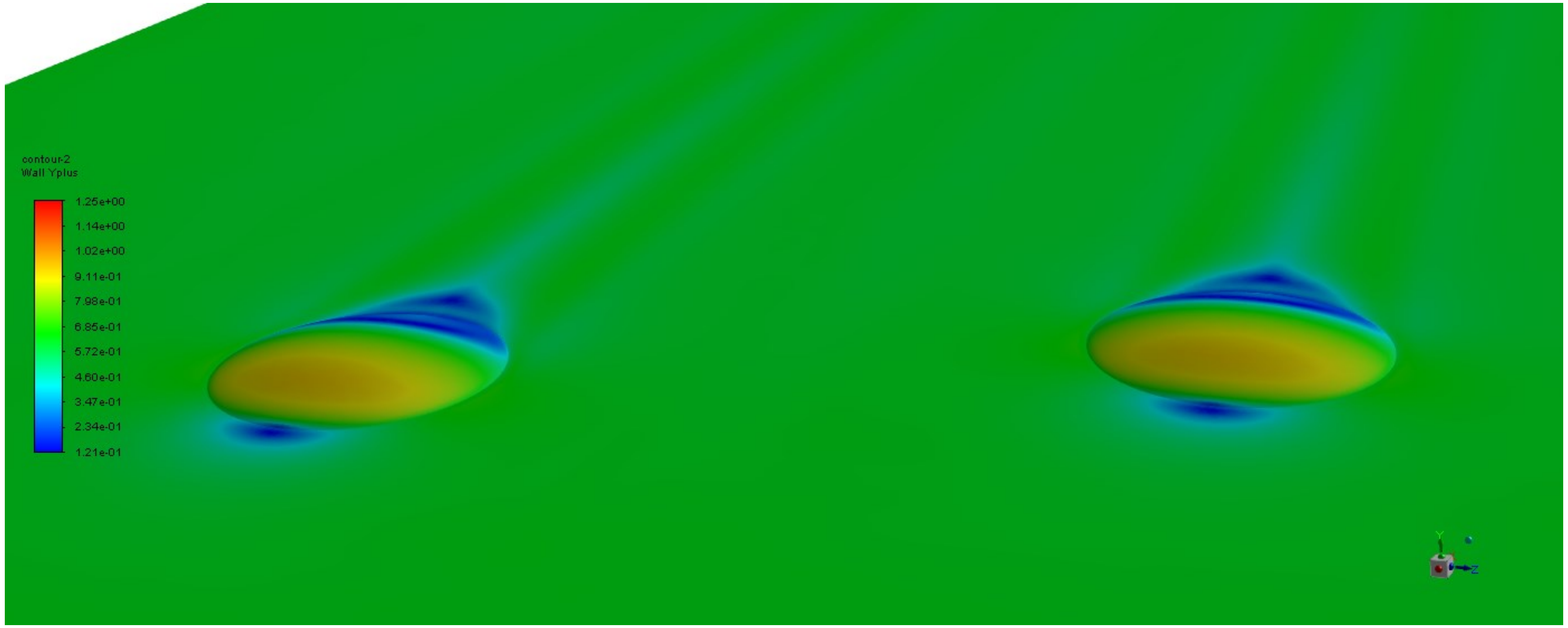
The mesh is first generated on surfaces and then the whole volume is filled using polyhedrons and hexahedrons

Setup

3D

- Operating conditions are the same as before (Re=1 000 000), incompressible, steady regime
- Pressure based solver, double precision
- Turbulence model: SST- kω, curvature correction, production limiter
- BCs:
  - Velocity *inlet*: v=40m/s directed along X- axis , I_t=1% , μ/μ_T =2
  - Pressure *outlet*: gauge pressure 0, operating pressure 101325 Pa
  - Symmetry walls: *top*, *entrance*
  - Periodic (translationally): *left* and *right*, set by making them as «interfaces» and prompting *«define>mesh-interfaces<make- periodic…»*
  - No-slip walls: *dev1, dev2, IndZone, plate*
- Pressure- velocity coupling: COUPLED, pseudo-transient, warped face gradient correction
- URFs: default, set «1» to «0.9»
- Reports:
  - Drag forces on each surface
  - integral of x-Wall shear stress on *dev1*, *dev2*
  - wall y+ (min, max, average)
  - mass flow rate imbalance (inlet-outlet and left-right)
- Initialization using a converged single pimple solution on a coarser mesh
- Run 140 iterations or less (continuity converge to 10^{-6} and reports to the 8° decimal place at least, monotonically)





3D

- Wall resolving approach: everywhere 0,1 < wall y+ < 2
- R_L contours show that the vortices are captured but the detachment zone should be resolved better (affordability?)

Results and optimization

3D

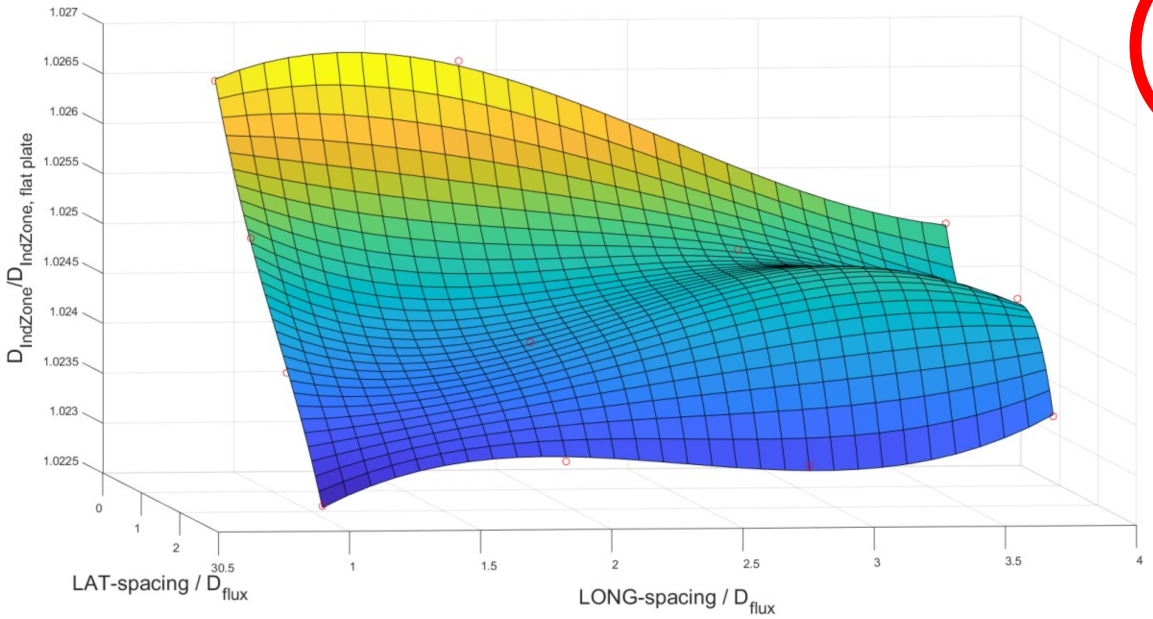
- The central composite DOE was designed to capture the zones where major variations of τ, interactions between the vortices and between pressure fields occur; that is the range 5-20 mm longitudinally and 0-15mm laterally

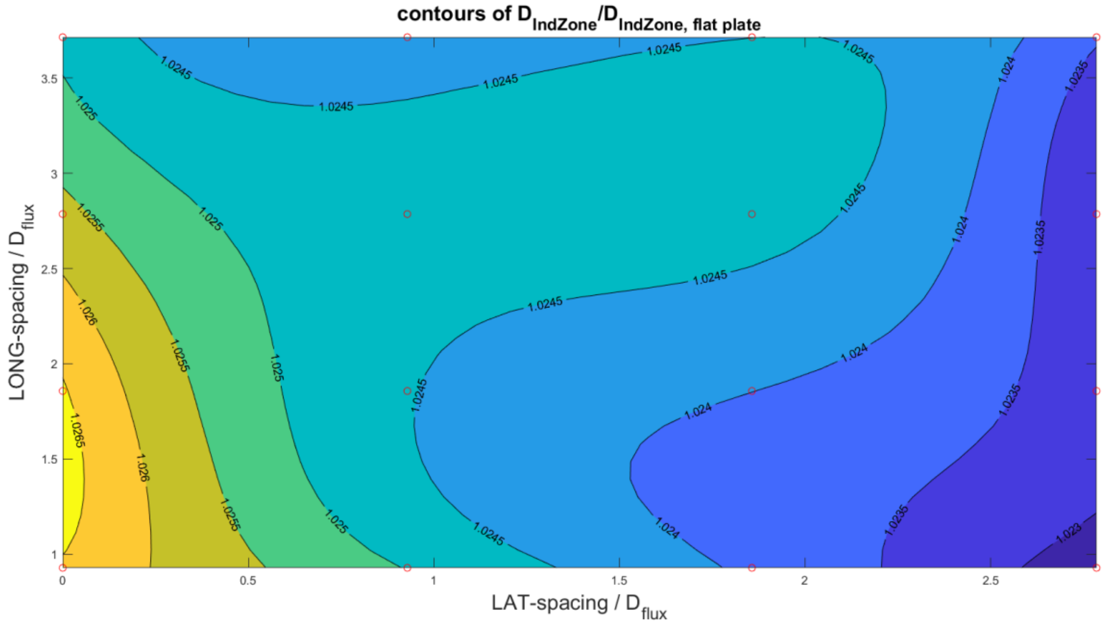
- 16 DOE points are evaluated and a least-square, 4° order RSM is generated

- There is a local minimum and a global minimum: worst cases occur in the «in-line» configuration.

- The lateral spacing has a strongly non-linear influence on drag

- Drag is always higher than the flat plate case





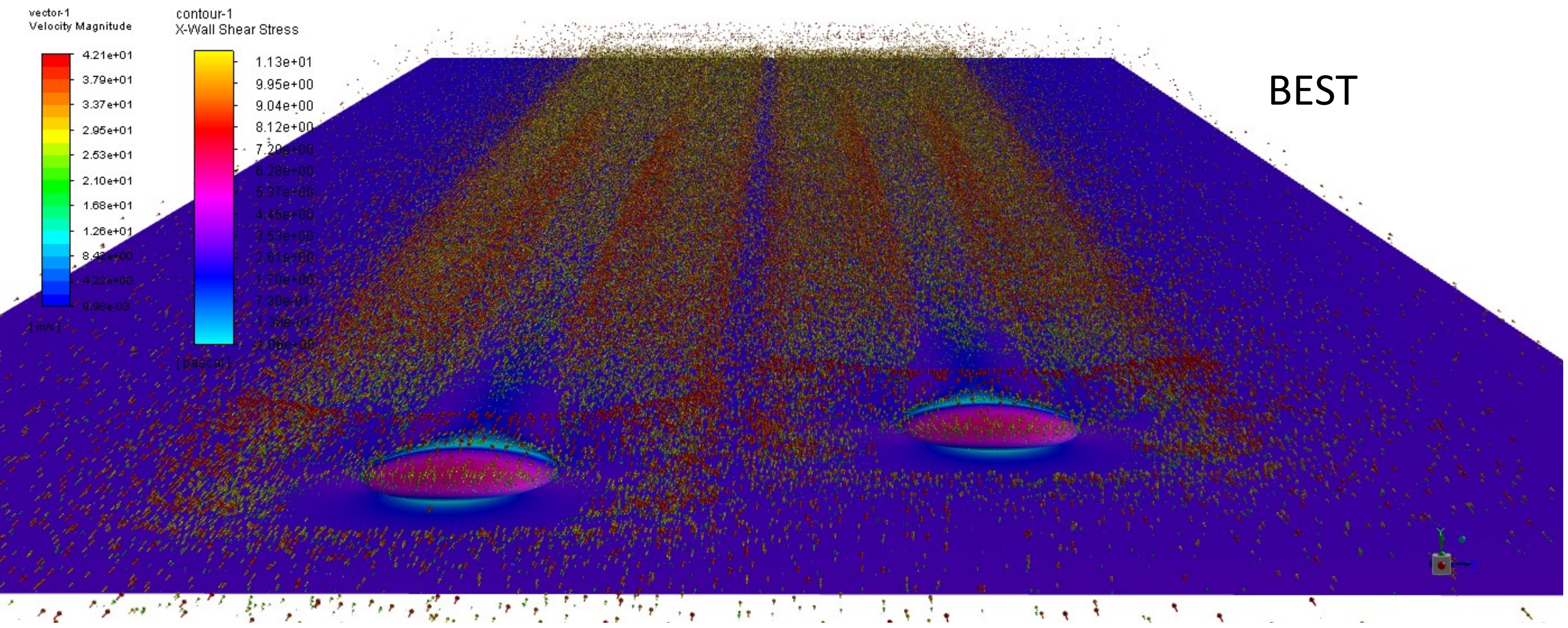
3D

	$C_{Dv,dev1}$	$C_{Dv,dev2}$	$C_{Dp,dev1}$	$C_{Dp,dev2}$	$C_{D,dev1}$	$C_{D,dev2}$	$C_{D,IZ-tot}$
best	7,78E-06	7,73E-06	6,28E-06	6,09E-06	1,41E-05	1,38E-05	2,03E-03
worst	7,68E-06	7,43E-06	5,31E-06	6,99E-06	1,30E-05	1,44E-05	2,04E-03
var %	+1,40%	+4,08%	+18,17%	-12,89%	+8,26%	-4,15%	-0,38%

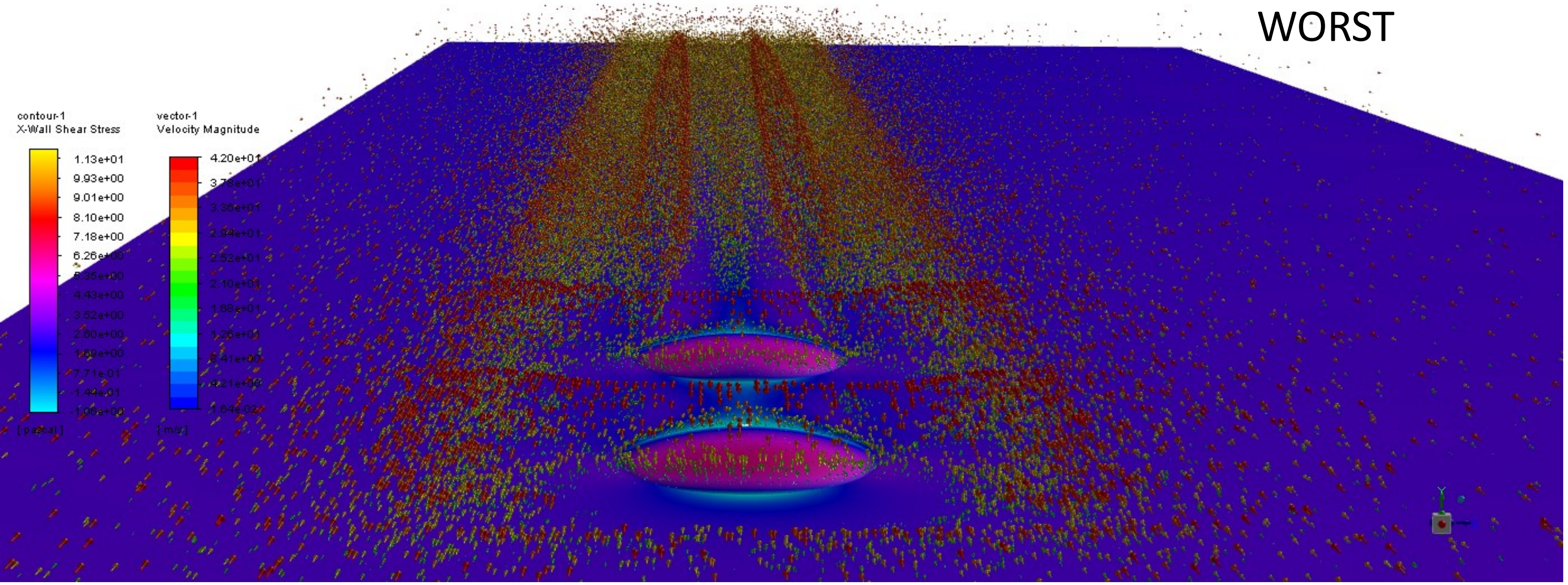
- Variations are counterintuitive but can be justified according to incompressible theory
- Deterioration in drag on the devices is won by a global improvement of drag on the flat plate behind the devices, which is much lower in percentage but acts on a much wider surface

3D

BEST

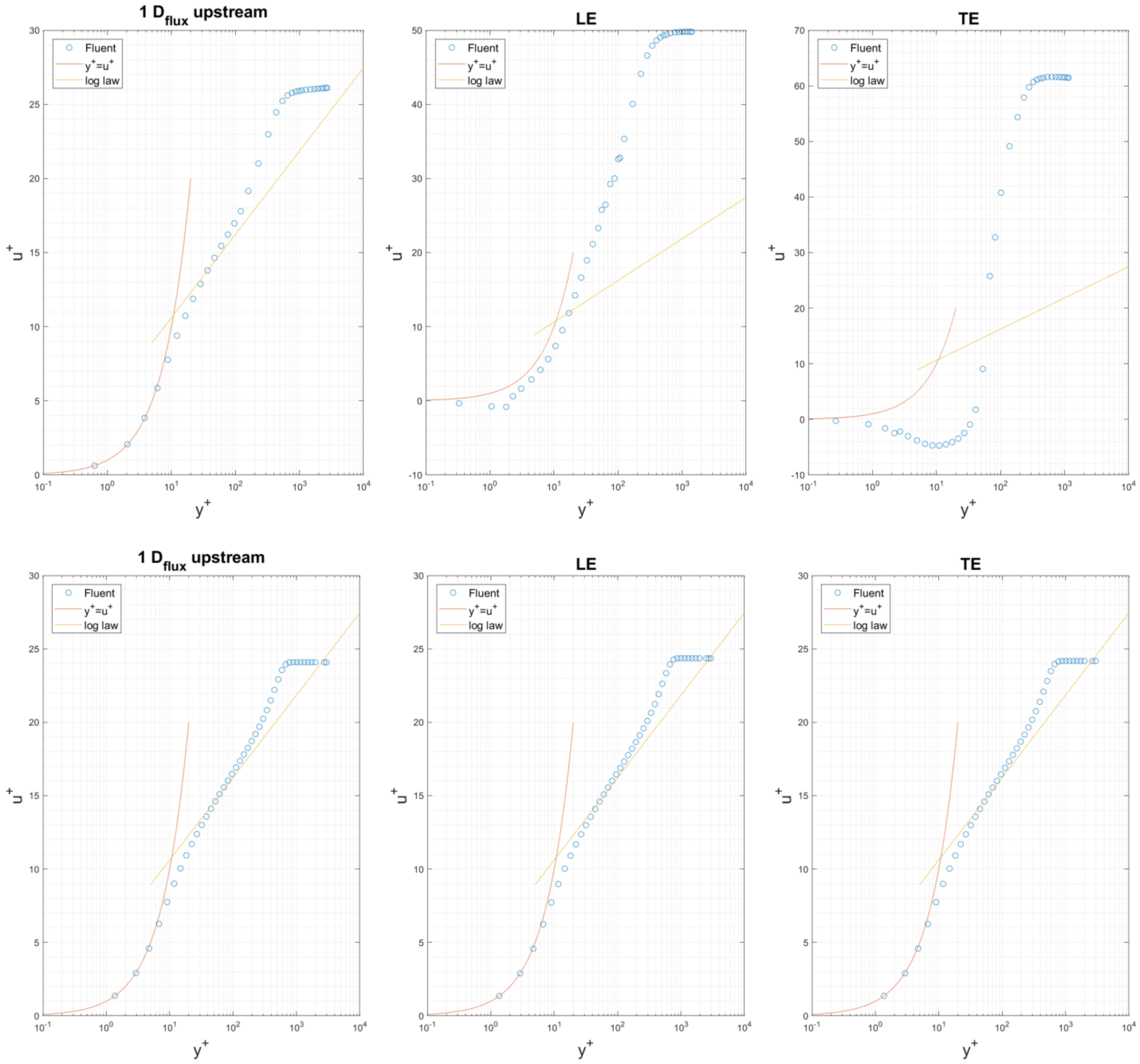


WORST



- X wall shear stress «striped» contours: where air is pulled up, there τ goes down, where air is pushed down, there τ increases

- Interaction between vortices and pressure field



3D

Plots of $u^+(y^+)$ show that

- where pressure gradients do not have a significant influence there is a very good agreement with theoretical profiles
- Where there is a favourable pressure gradient, the plot goes upper then the log- law line
- Where local detachment occurs, there the profile goes negative

WHAT IS THE OPTIMAL SHAPE ?

Why the Adjoint?

2D 3D

ADVANTAGES

- It can be applied to the Turbulence model that we used (k-w SST);
- It has a low computational cost in respect to other optimization methods, like the gradient based;

DRAWBACKS

- Sensitivity map isn’t easy to understand;
- It can generate non-physical shape morphing, negative volumes and deform so much the mesh to have in the end a low quality result;
- Solution of the adjoint must be really well converged and this isn’t always easy to have.

2D Shape optimization using Fluent Adjoint Solver

2D

SETUP

Pimple's shape was optimized using the adjoint method. The setup is:

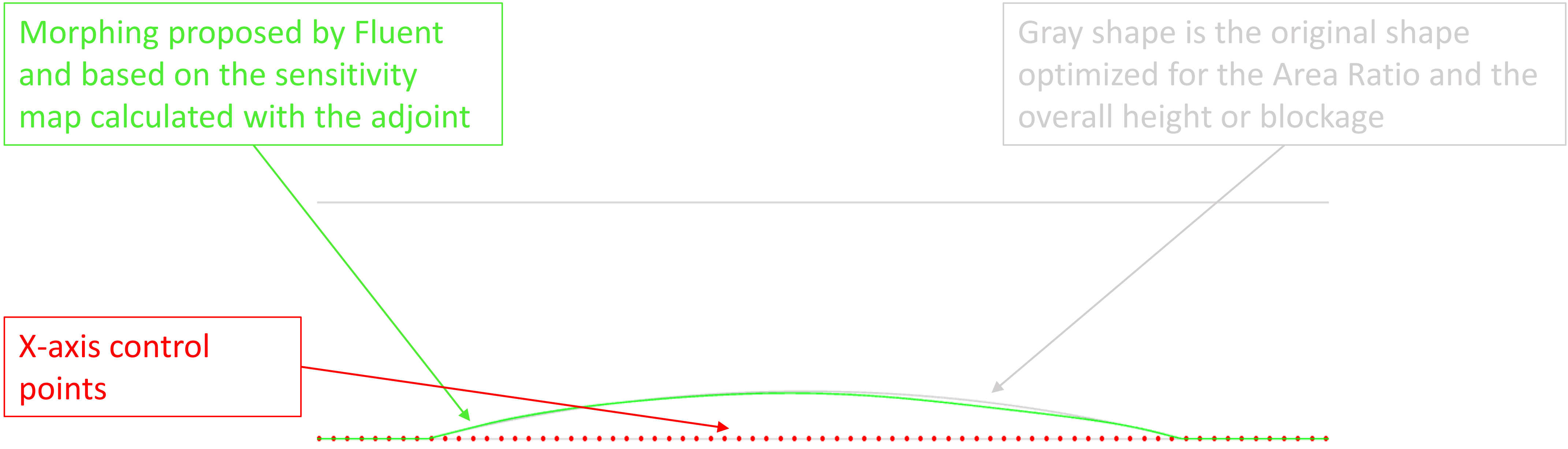
- As force observable it was chosen the wall and the objective orientation was set to minimize;
- Solution method: Gauss-Green cell based with default options for pressure and momentum;
- Convergence criteria of the adjoint set to 10^{-6} for continuity and adjoint, default for local flow rate;

For each iteration the desired change of the drag was kept low because it easily ended up with negative volumes when higher single step decreases were required.

2D Shape optimization using Fluent Adjoint Solver

RESULTS

1) First iteration → desired drag reduction of 0,5%.



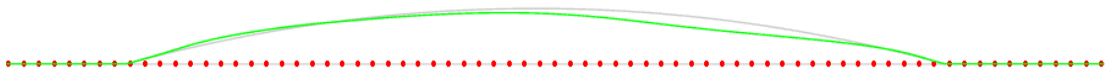
2D Shape optimization using Fluent Adjoint Solver

RESULTS

Two more iterations were run:

1) the first, this time, with a desired drag reduction of 1%:

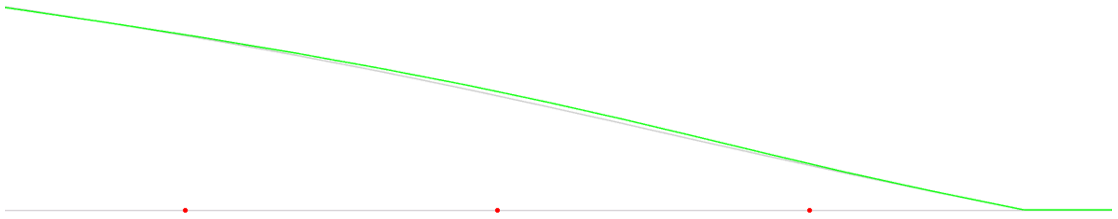
   for each iteration the drag reduction couldn’t be much higher because it caused the generation of not physical shapes or even negative volumes.



$-0,3\%\ of\ C_D$

2) the second iteration with the same desired reduction;

   the shape didn’t change a lot, it just became flatter and more rear slanted as it can be seen in the second figure.



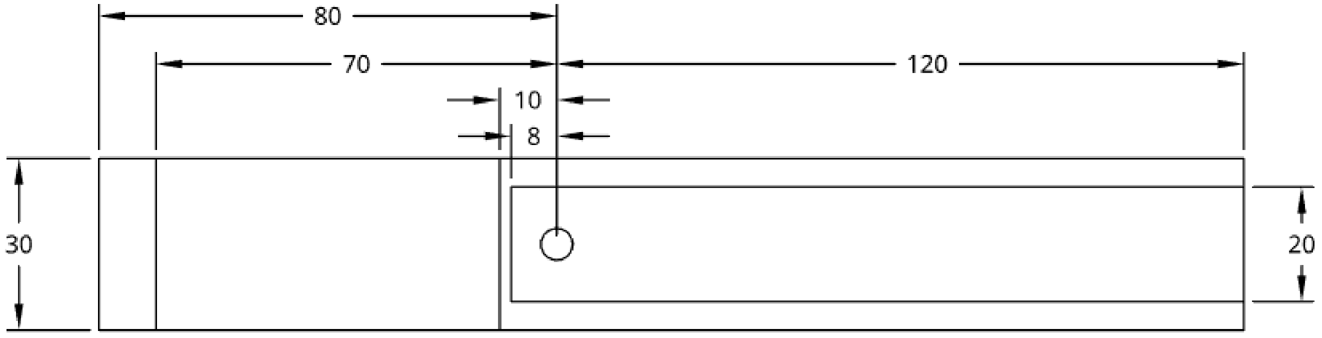
$-0,5\%\ of\ C_D$

3D Shape optimization using Fluent Adjoint Solver

3D

As the analysis of a double pimpled surface suggests that the optimal configuration is when the two pimples are non- interferent (single line of laterally spaced pimples), it makes no sense to study the optimal shape of the first and the second pimple separately

Study a simplified 1-pimple case with reduced cell count (750 000 poli-hexa cells)



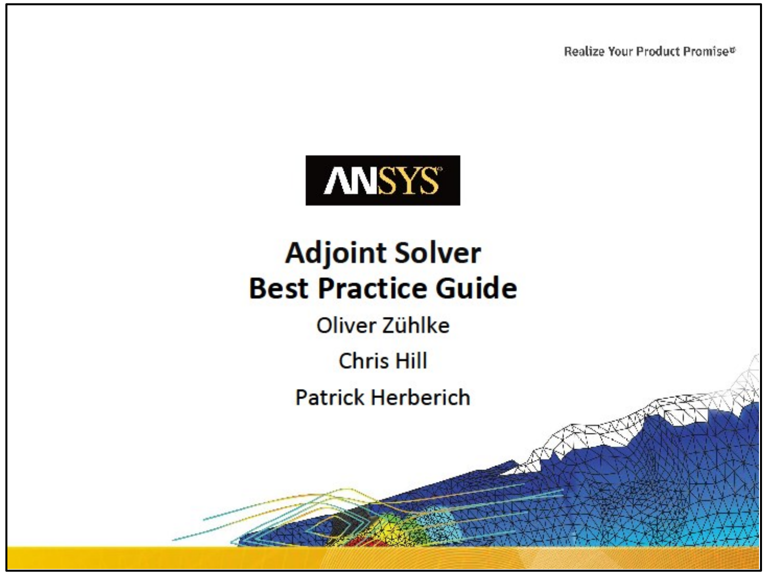
Setup

3D

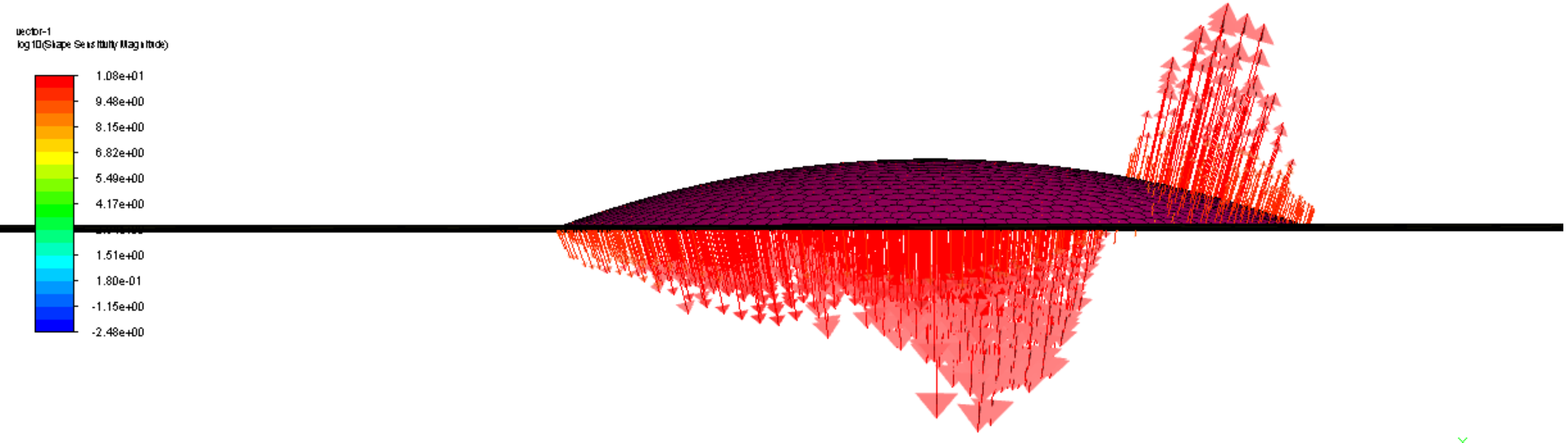
The direct simulation setup is the same as in the previous computations

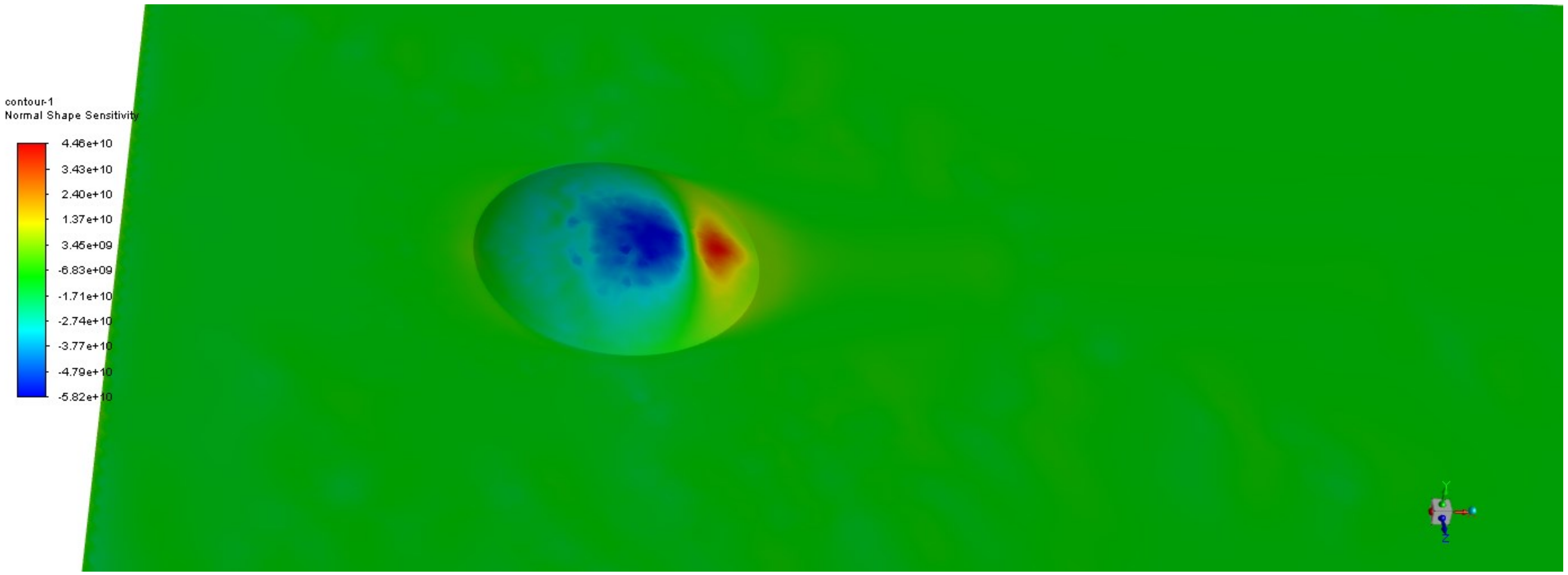
The Adjoint solution requires a well converged direct solution first, then

1. Create an observable for the drag on the IndZone and set to «minimize»
2. Set solution methods as:
    1. Method: Green-Gauss node based
    2. Pressure: standard
    3. Momentum: first order
3. Set continuity monitor to 10^{-6} or less
4. Start computation with default stabilization techniques, then follow *P. Herberich O. Zuhlke* guide until convergence



3D





Sensitivity to shape maps:

to minimize drag the surface should be flattened and made «drop-like»

RESULTS

- pressure drag must be taken into account making flatter devices. Blockage height is the dominant parameter when dealing with pressure drag both in 2D and 3D;

- single pimple generate a horseshoe vortex that is steady, very stable and divides the downstream zone into stripes where viscous drag is alternatively improved or worsened; single dimple devices generate cyclone-like vortices or more complicated patterns that show more unsteadiness;

- the double-device case, under the (reasonable) assumption that the case PP is the best among the other configurations, turns out to be optimal when there is a single row of pimples: P and PP seem both in 2D and 3D the best cases for a flat-plate;

- the optimal shape of a single pimple is confirmed both in 2D and 3D adjoint calculations: to reduce the drag the pimple should be "flattened and rear-slanted". If more adjoint iterations were run, the result would be probably brought to the extreme of recreating a flat plate;

- interactions between wakes or pressure gradients should be avoided as much as possible because, at least on a flat plate, they don't guarantee any advantage, causing a higher viscous drag behind the pimples. On a diffuser there may –reasonably- be more interesting interactions.

END OF OUR PRESENTATION

THANK YOU

FOR YOUR ATTENTION !