CHRISTMAS CHALLENGE 2021

Evaluation of the drag coefficient of a sphere

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STARTING POINTS

About me:

-Approximately 6 months of CFD experience in Comsol and OpenFOAM

-Working as a consultant in hydrodynamics and morphology based in the Netherlands

-A big fan of the toturial clips by József!

About the simulations:

-OpenFOAM v1812 (linux)

-Runs performed on linux-cluster (16 cpu per run)

-Post-processing done in Python

Study objective:

Determine the drag coefficient Cd of a sphere and compare this to experimental fits

MESHING

Meshing is performed using snappyHexMesh

The mesh includes:

-Domain of 40m x 10m x 10m

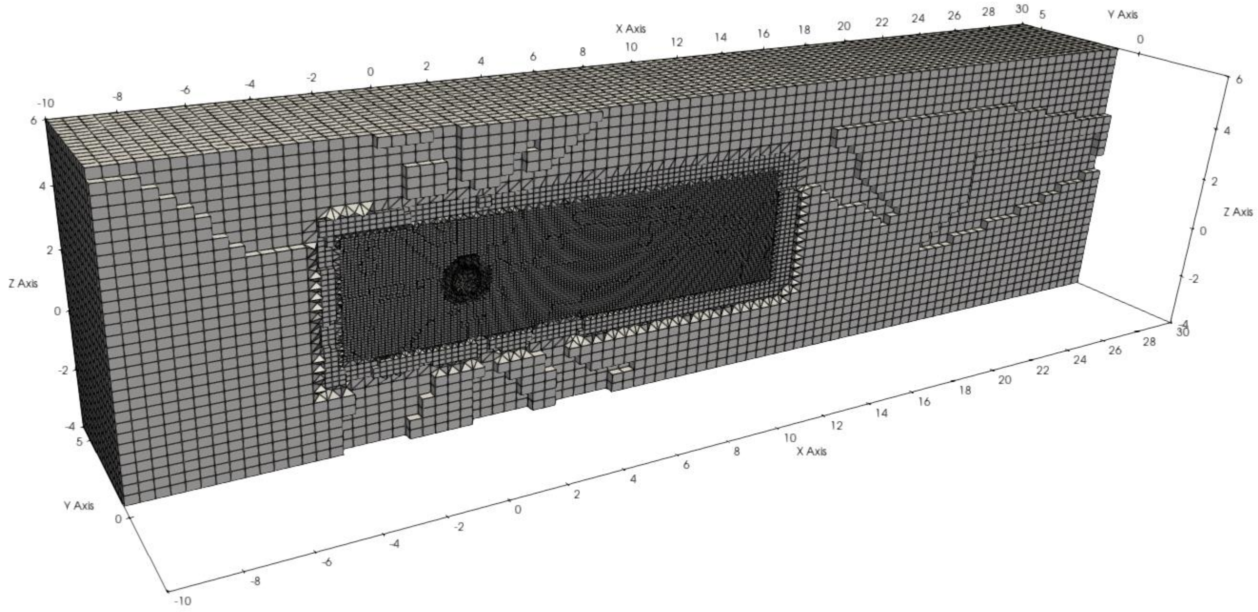
-Background mesh – cell size: 0.44m x 0.3m x 0.3m

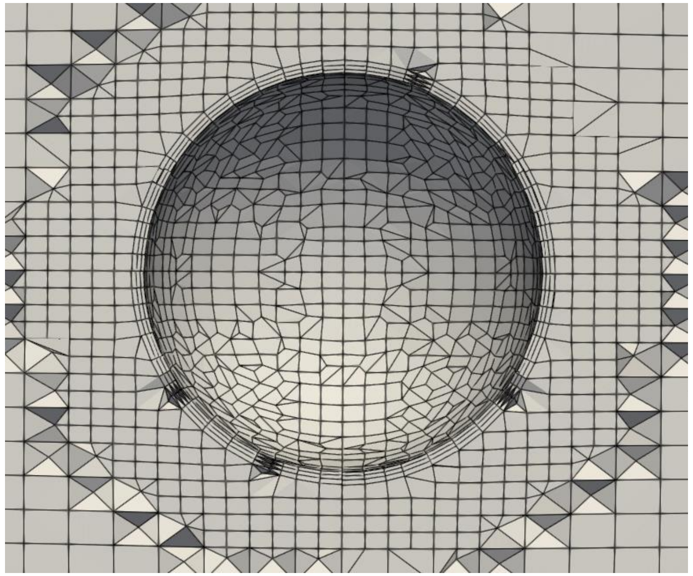
-One refinement zone (level 2)

-One refined surface around the sphere (level 3)

-3 boundary layers with an expansion ratio of 1.2, minimum thickness of 0.1 and final thickness of 0.3

-in total 627,533 cells





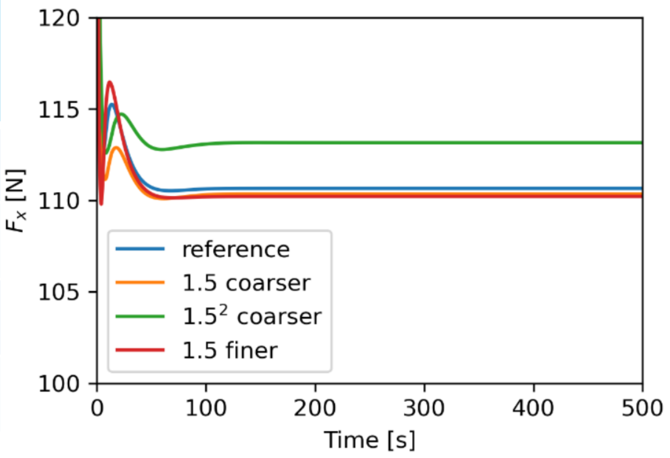
MESHING

Grid sensitivity step to check whether the grid is ‘fine enough’

For this I selected the case for Re = 1 and ρ = 1,000 kg/m3

I evaluate the force in streamwise direction on the sphere for the used grid (reference), two coarser grids and one finer grid

Coarseness factor (in all directions)	**Force x (after 500 seconds of spinup)**
$1{,}5^2$ coarser	113,15 N
1,5 coarser	110,35 N
Reference	110,65 N
1,5 finer	110,21 N

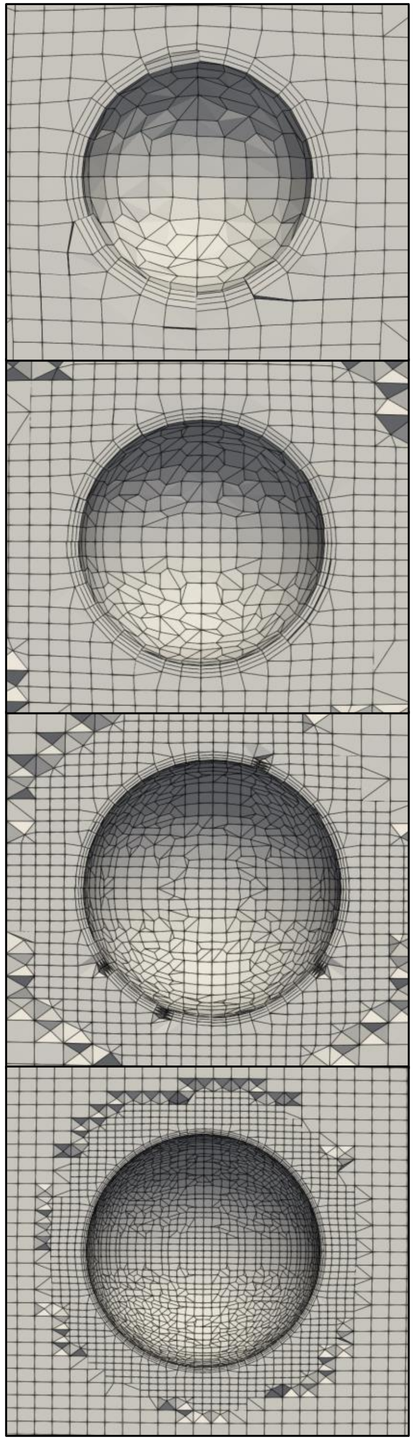


$1{,}5^2$ coarser

1,5 coarser

reference

1,5 finer



SIMULATION CASES

Dependency on the Reynolds number: $\mathrm{Re} = \frac{U * L}{v}$

To prevent excessive computational time, I varied v instead of U (due to CFL-condition)

→ this might lead to unrealistic fluid properties, but this serves this exercise nonetheless

I selected the k-ω-SST turbulence model (hybrid RANS model which uses k-ε in free-stream zone and k-ω near the walls of the sphere)

Boundary and initial conditions are determined using the following set of equations:

Turbulent kinetic energy: $k = \frac{3}{2}(|\mathbf{U}|I_T)^2$ low turbulence: It = 0,01; medium turbulence: It = 0,01-0,05; high turbulence: It = 0,05-0,20 [2]

Omega: $\omega = \frac{\sqrt{k}}{(\beta_0^*)^{1/4} L_T}$ $\beta_0^* = \frac{9}{100}$ $L_T \cong 0{,}07 * L_D$, $L_D \cong 0{,}5 * Diameter\ sphere$

Turbulent viscosity vt $\nu_t = \frac{k}{\omega}$ [1]

References:

[1] COMSOL (2020). CFD Module User Manual. Version 5.6

[2] https://www.cfd-online.com/Wiki/Turbulence_intensity

SIMULATION CASES

The following set of simulation cases are defined, including the different boundary settings for the sphere:

Simulation	Reynolds number	Kinematic viscosity	Turbulence intensity	U (inlet)	K (sphere)	ω (sphere)	νt,ω (sphere)
1	0,01	1 e+1	0,01	(0,1 0 0)	1,5 e-6	4,47 e-3	3,35 e-4
2	0,1	1 e-0	0,01	(0,1 0 0)	1,5 e-6	4,47 e-3	3,35 e-4
3	1	1 e-1	0,01	(0,1 0 0)	1,5 e-6	4,47 e-3	3,35 e-4
4	10	1 e-2	0,02	(0,1 0 0)	6,0 e-6	8,94 e-3	6,71 e-4
5	100	1 e-3	0,03	(0,1 0 0)	1,35 e-5	1,34 e-2	1,01 e-3
6	1000	1 e-4	0,05	(0,1 0 0)	3,75 e-5	2,24 e-2	1,68 e-3
7	10000	1 e-5	0,12	(0,1 0 0)	2,16 e-4	5,37 e-2	4,02 e-3
8	100000	1 e-6	0,15	(0,1 0 0)	3,38 e-4	6,71 e-2	5,03 e-3
9	1000000	1 e-7	0,18	(0,1 0 0)	4,56 e-4	8,05 e-2	6,04 e-3

$$k = \frac{3}{2}(|\mathbf{U}| I_T)^2 \qquad \omega = \frac{\sqrt{k}}{(\beta_0^*)^{1/4} L_T} \qquad \nu_t = \frac{k}{\omega}$$

RESULTS

For Re $< 10^3$ a spinup time of 1,000 seconds is sufficient. For Re $\geq 10^3$ a spinup time between 10,000 and 25,000 seconds is applied. The results are averaged over the last 500 time steps

The simulated drag coefficients are compared to experimental fits:

-Oseen [1] for Re < 0.4

$$C_D = \frac{24}{Re}\left(1 + \frac{3}{16}Re\right)$$

-Clift and Gauvin [2] for 0.4<Re<10,000

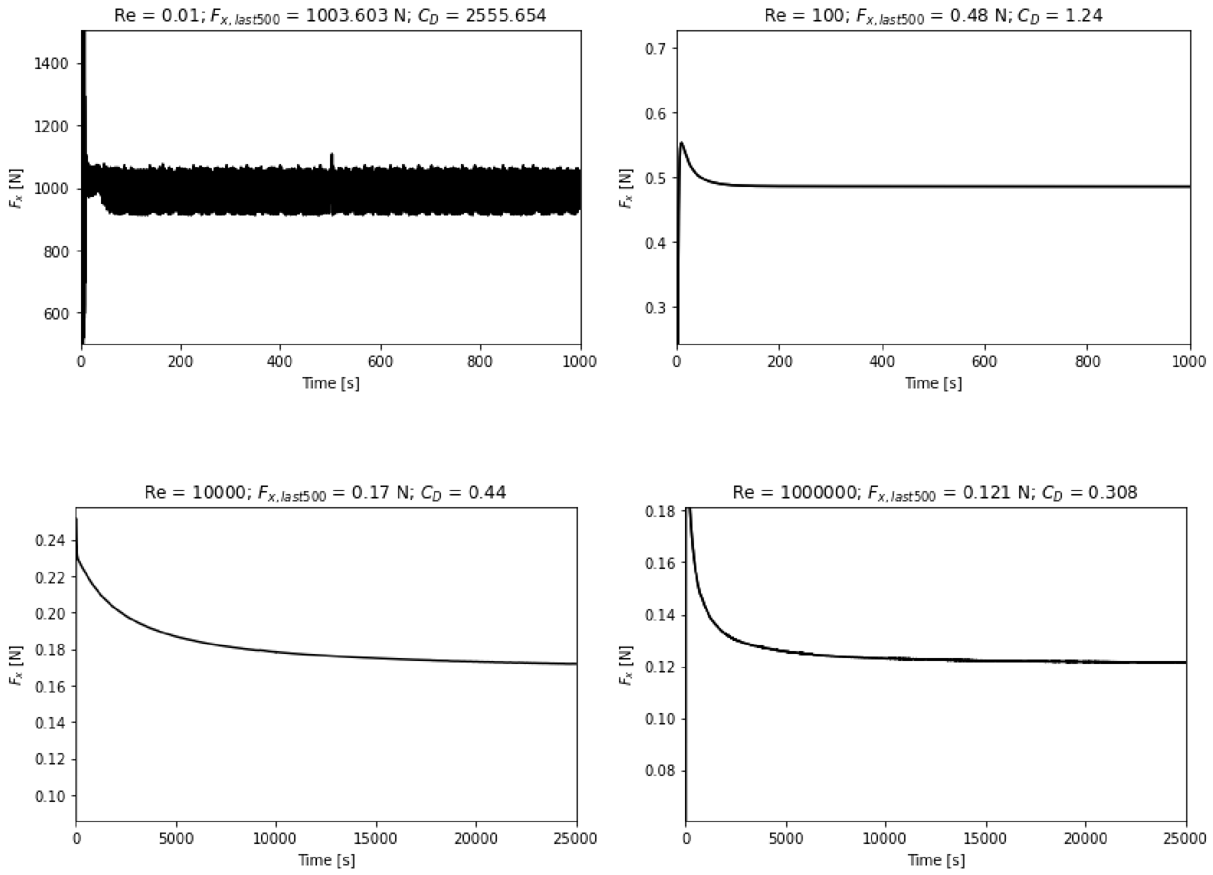
$$C_D = \frac{24}{Re}\left(1 + 0.15Re^{0.687}\right) + \frac{0.42}{1 + \frac{42500}{Re^{1.16}}}$$

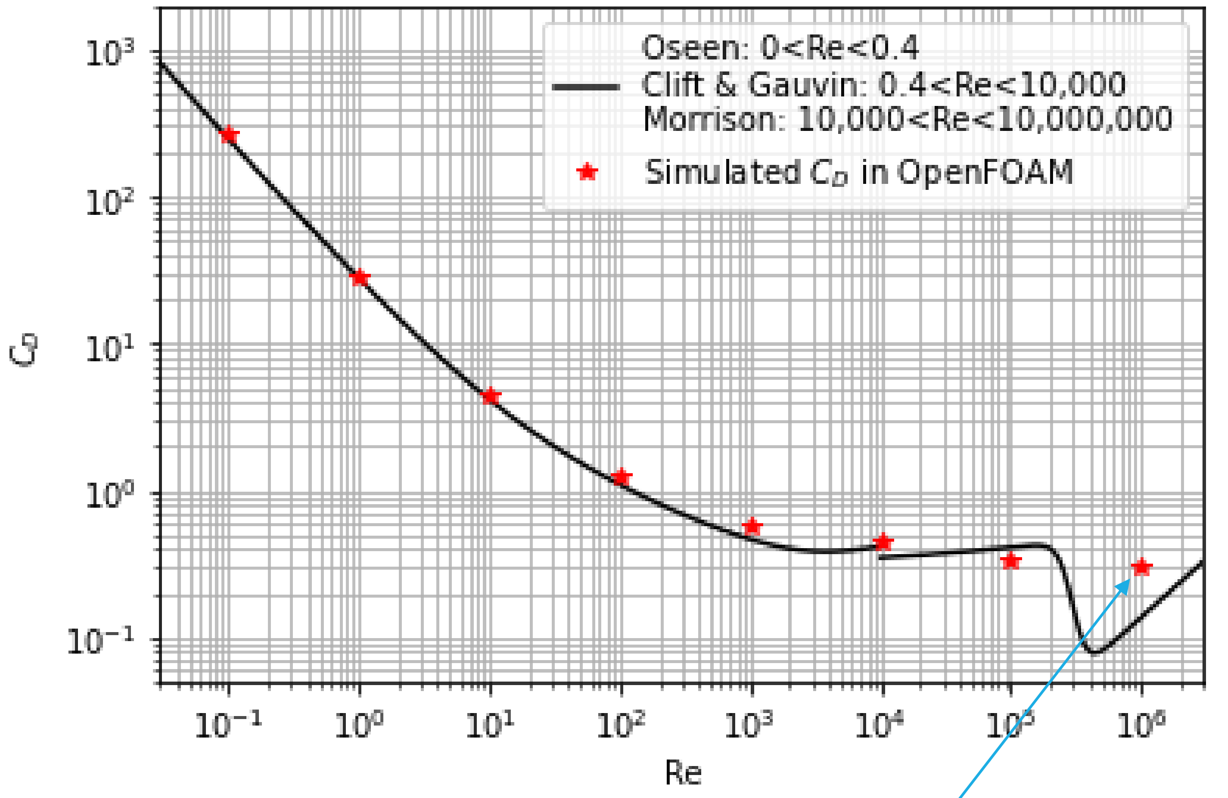
-Morrison [3] for 10,000<Re<10,000,000

$$C_D = \frac{24}{Re} + \frac{2.6\left(\frac{Re}{5.0}\right)}{1 + \left(\frac{Re}{5.0}\right)^{1.52}} + \frac{0.411\left(\frac{Re}{263,000}\right)^{-7.94}}{1 + \left(\frac{Re}{263,000}\right)^{-8.00}} + \left(\frac{Re^{0.80}}{461,000}\right)$$

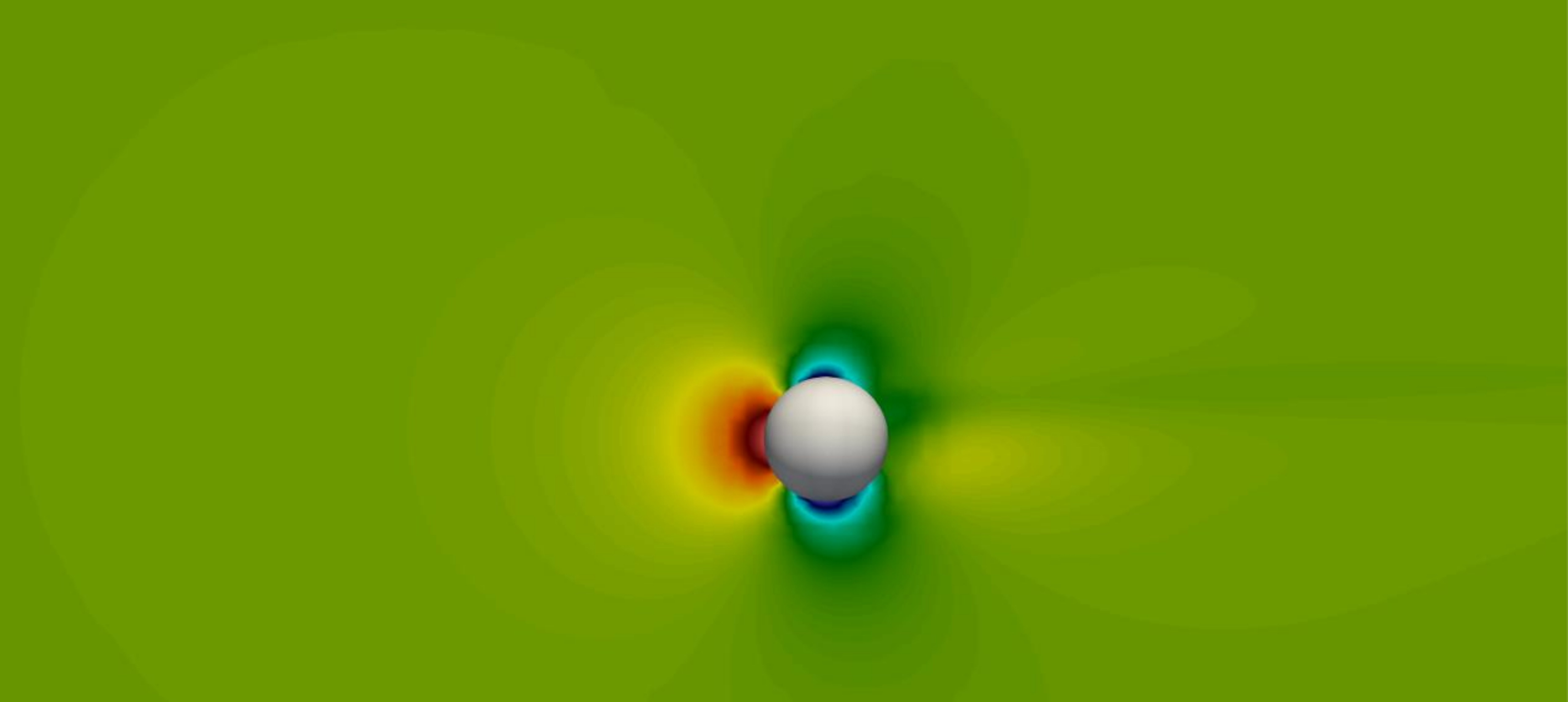
References:
[1] C.W. Oseen (1910). Über die Stokessche Formel und die verwandte Aufgabe in der Hydrodynamik. *Arkiv Mat. Astron. Phsik.*, 6 pp. 29
[2] R. Clift and W. H. Gauvin. Motion of entrained particles in gas streams. *The Canadian Journal of Chemical Engineering*, 49(4) pp. 439–448, August 1971
[3]. F.A. Morrison (2013). Data correlation for Drag Coefficient of Sphere

RESULTS





Outside applicability range of RANS model?



MERRY XMAS AND A HAPPY AND HEALTHY 2022!

APPENDIX - SIMULATION CASES

The following boundary condition types are applied at the domain boundaries

Simulation	U	p	k	ω	νt,ω
Inlet	fixedValue Value uniform (0.1 0 0)	zeroGradient	zeroGradient	zeroGradient	Calculated
Outlet	inletOutlet Value uniform (0 0 0)	fixedValue Value uniform 0	zeroGradient	zeroGradient	Calculated
Front	zeroGradient	zeroGradient	zeroGradient	zeroGradient	Calculated
Back	zeroGradient	zeroGradient	zeroGradient	zeroGradient	Calculated
Top	zeroGradient	zeroGradient	zeroGradient	zeroGradient	Calculated
Bottom	zeroGradient	zeroGradient	zeroGradient	zeroGradient	Calculated
Sphere	noSlip	zeroGradient	kqRWallFunction Value from next slide 6	omegaWallFunction Value from next slide 6	nutkWallFunction Value from next slide 6