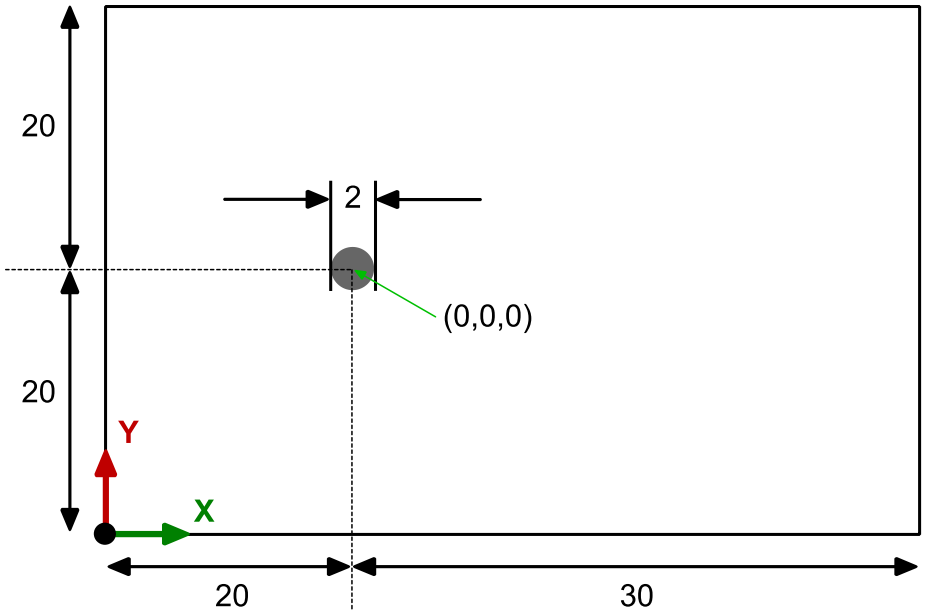
Flow past a cylinder – From laminar to turbulent flow

Flow around a cylinder – 10 < Re < 2 000 000
Incompressible and compressible flow



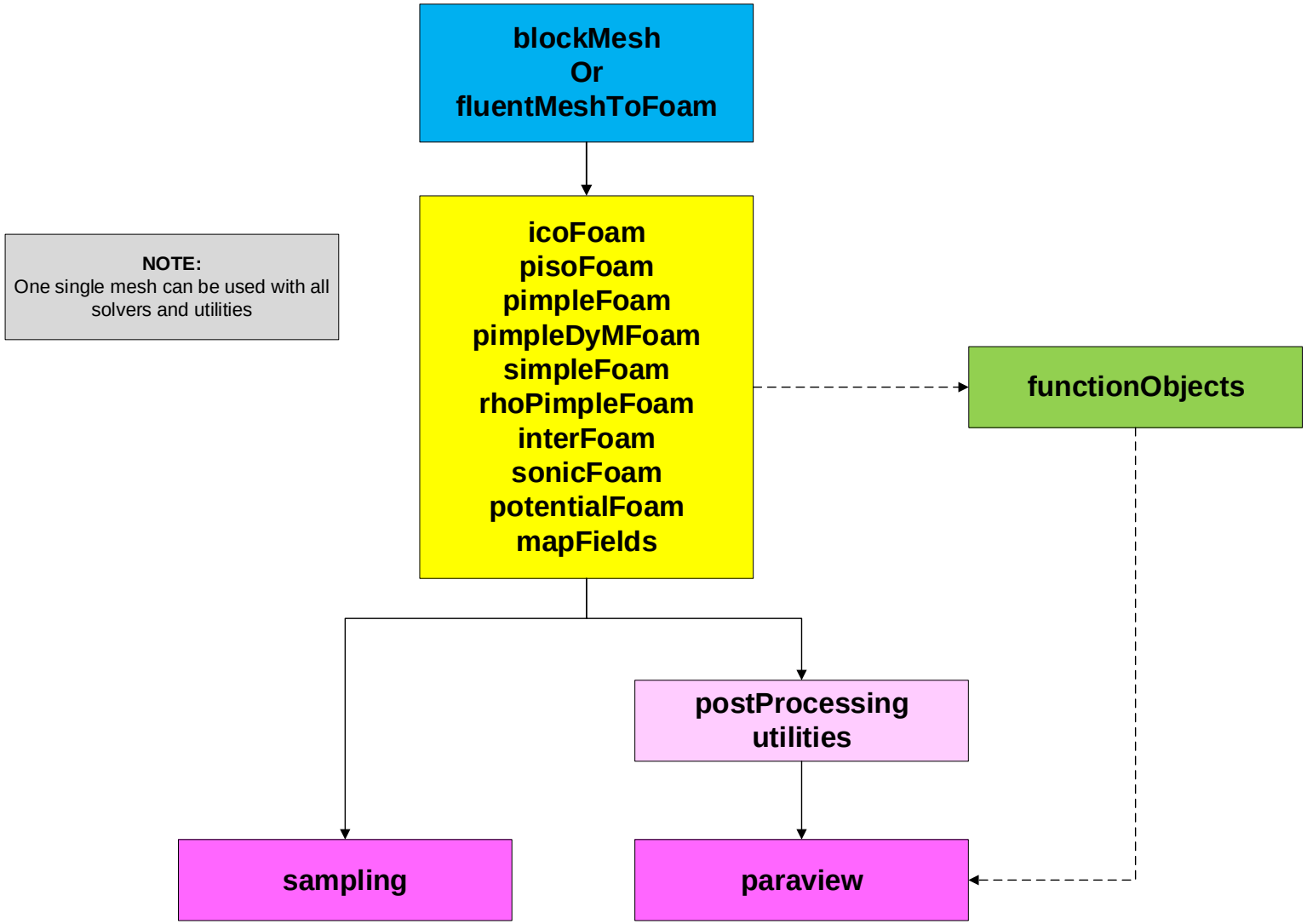
All the dimensions are in meters

Physical and numerical side of the problem:

- In this case we are going to solve the flow around a cylinder. We are going to use incompressible and compressible solvers, in laminar and turbulent regime.
- Therefore, the governing equations of the problem are the incompressible/compressible laminar/turbulent Navier-Stokes equations.
- We are going to work in a 2D domain.
- Depending on the Reynolds number, the flow can be steady or unsteady.
- This problem has a lot of validation data.

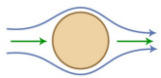
Flow past a cylinder – From laminar to turbulent flow

Workflow of the case



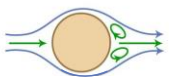
Flow past a cylinder – From laminar to turbulent flow

Vortex shedding behind a cylinder



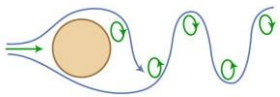
Creeping flow (no separation)
Steady flow

$Re < 5$



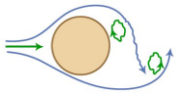
A pair of stable vortices in the wake
Steady flow

$5 < Re < 40 - 46$



Laminar vortex street (Von Karman street)
Unsteady flow

$40 - 46 < Re < 150$

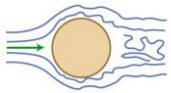


Laminar boundary layer up to the separation point, turbulent wake
Unsteady flow

$150 < Re < 300$

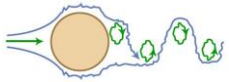
Transition to turbulence

$300 < Re < 3 \times 10^5$



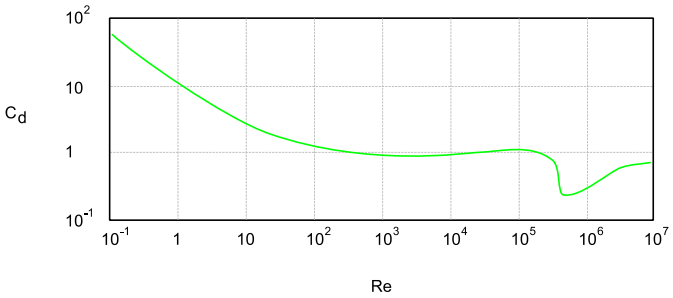
Boundary layer transition to turbulent
Unsteady flow

$3 \times 10^5 < Re < 3 \times 10^6$

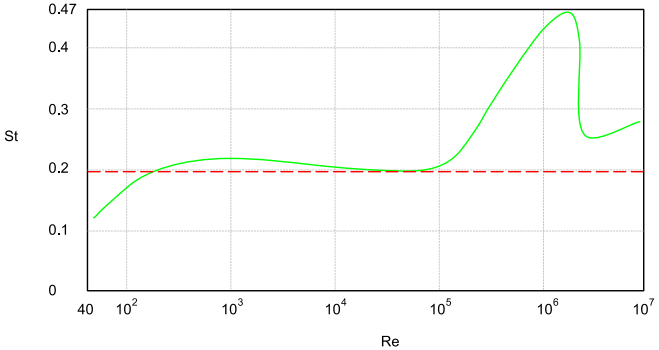


Turbulent vortex street, but the wake is narrower than in the laminar case
Unsteady flow

$3 \times 10^6 > Re$



Drag coefficient



Strouhal number

Flow past a cylinder – From laminar to turbulent flow

Some experimental (E) and numerical (N) results of the flow past a circular cylinder at various Reynolds numbers

Reference	c_d – Re = 20	L_{rb} – Re = 20	c_d – Re = 40	L_{rb} – Re = 40
[1] Tritton (E)	2.22	–	1.48	–
[2] Cuntanceau and Bouard (E)	–	0.73	–	1.89
[3] Russel and Wang (N)	2.13	0.94	1.60	2.29
[4] Calhoun and Wang (N)	2.19	0.91	1.62	2.18
[5] Ye et al. (N)	2.03	0.92	1.52	2.27
[6] Fornbern (N)	2.00	0.92	1.50	2.24
[7] Guerrero (N)	2.20	0.92	1.62	2.21

L_{rb} = length of recirculation bubble, **c_d** = drag coefficient, **Re** = Reynolds number,

[1] D. Tritton. Experiments on the flow past a circular cylinder at low Reynolds numbers. Journal of Fluid Mechanics, 6:547-567, 1959.
[2] M. Cuntanceau and R. Bouard. Experimental determination of the main features of the viscous flow in the wake of a circular cylinder in uniform translation. Part 1. Steady flow. Journal of Fluid Mechanics, 79:257-272, 1973.
[3] D. Rusell and Z. Wang. A cartesian grid method for modeling multiple moving objects in 2D incompressible viscous flow. Journal of Computational Physics, 191:177-205, 2003.
[4] D. Calhoun and Z. Wang. A cartesian grid method for solving the two-dimensional streamfunction-vorticity equations in irregular regions. Journal of Computational Physics. 176:231-275, 2002.
[5] T. Ye, R. Mittal, H. Udaykumar, and W. Shyy. An accurate cartesian grid method for viscous incompressible flows with complex immersed boundaries. Journal of Computational Physics, 156:209-240, 1999.
[6] B. Fornberg. A numerical study of steady viscous flow past a circular cylinder. Journal of Fluid Mechanics, 98:819-855, 1980.
[7] J. Guerrero. Numerical simulation of the unsteady aerodynamics of flapping flight. PhD Thesis, University of Genoa, 2009.

Flow past a cylinder – From laminar to turbulent flow

Some experimental (E) and numerical (N) results of the flow past a circular cylinder at various Reynolds numbers

Reference	c_d – Re = 100	c_l – Re = 100	c_d – Re = 200	c_l – Re = 200
[1] Russel and Wang (N)	1.38 ± 0.007	± 0.322	1.29 ± 0.022	± 0.50
[2] Calhoun and Wang (N)	1.35 ± 0.014	± 0.30	1.17 ± 0.058	± 0.67
[3] Braza et al. (N)	1.386± 0.015	± 0.25	1.40 ± 0.05	± 0.75
[4] Choi et al. (N)	1.34 ± 0.011	± 0.315	1.36 ± 0.048	± 0.64
[5] Liu et al. (N)	1.35 ± 0.012	± 0.339	1.31 ± 0.049	± 0.69
[6] Guerrero (N)	1.38 ± 0.012	± 0.333	1.408 ± 0.048	± 0.725

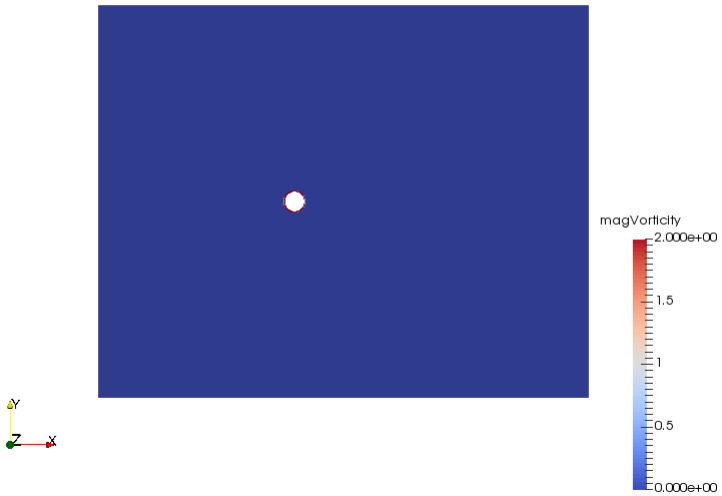
c_l = lift coefficient, **c_d** = drag coefficient, **Re** = Reynolds number

[1] D. Rusell and Z. Wang. A cartesian grid method for modeling multiple moving objects in 2D incompressible viscous flow. Journal of Computational Physics, 191:177-205, 2003.
[2] D. Calhoun and Z. Wang. A cartesian grid method for solving the two-dimensional streamfunction-vorticity equations in irregular regions. Journal of Computational Physics. 176:231-275, 2002.
[3] M. Braza, P. Chassaing, and H. Hinh. Numerical study and physical analysis of the pressure and velocity fields in the near wake of a circular cylinder. Journal of Fluid Mechanics, 165:79-130, 1986.
[4] J. Choi, R. Oberoi, J. Edwards, an J. Rosati. An immersed boundary method for complex incompressible flows. Journal of Computational Physics, 224:757-784, 2007.
[5] C. Liu, X. Zheng, and C. Sung. Preconditioned multigrid methods for unsteady incompressible flows. Journal of Computational Physics, 139:33-57, 1998.
[6] J. Guerrero. Numerical Simulation of the unsteady aerodynamics of flapping flight. PhD Thesis, University of Genoa, 2009.

Flow past a cylinder – From laminar to turbulent flow

At the end of the day, you should get something like this

Instantaneous velocity magnitude field
www.wolfdynamics.com/wiki/cylinder_vortex_shedding/movvmag.gif

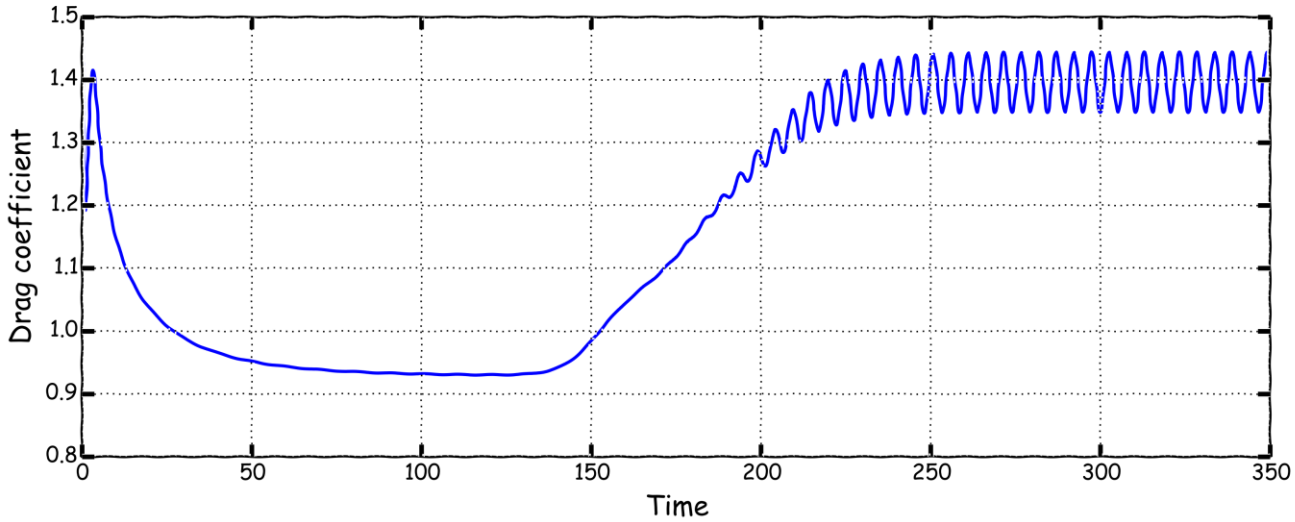


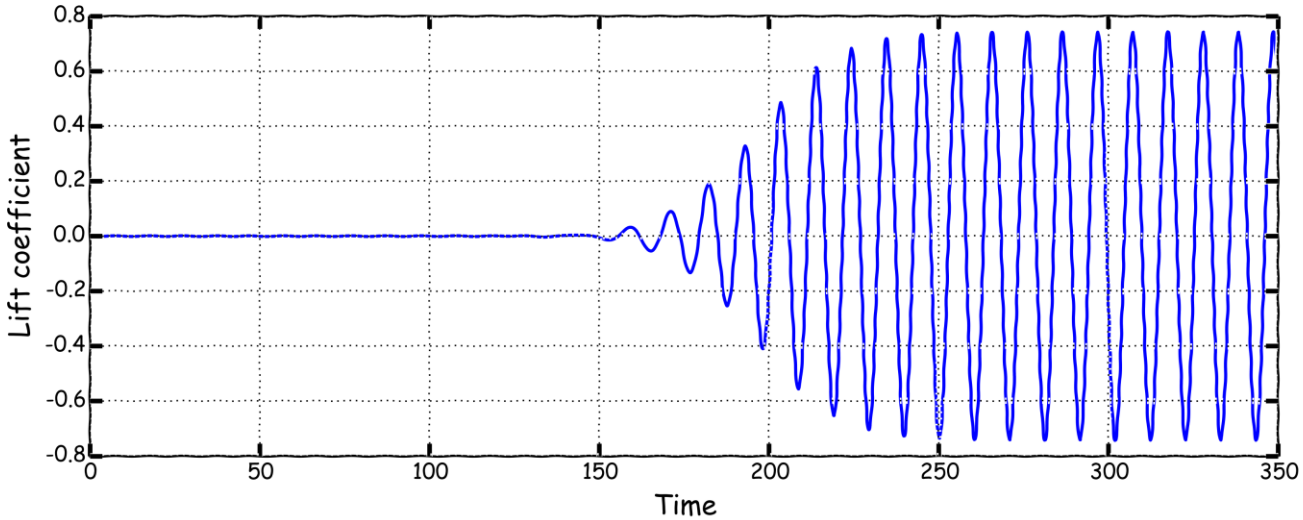
Instantaneous vorticity magnitude field
www.wolfdynamics.com/wiki/cylinder_vortex_shedding/movvort.gif

Incompressible flow – Reynolds 200

Flow past a cylinder – From laminar to turbulent flow

At the end of the day, you should get something like this





Incompressible flow – Reynolds 200

Flow past a cylinder – From laminar to turbulent flow

- Let us run this case. Go to the directory:

```
$PTOFC/vortex_shedding
```

- $PTOFC is pointing to the directory where you extracted the training material.
- In the case directory, you will find the `README.FIRST` file. In this file, you will find the general instructions of how to run the case. In this file, you might also find some additional comments.
- You will also find a few additional files (or scripts) with the extension .sh, namely, `run_all.sh`, `run_mesh.sh`, `run_sampling.sh`, `run_solver.sh`, and so on. These files can be used to run the case automatically by typing in the terminal, for example, `sh run_solver`.
- We highly recommend you to open the `README.FIRST` file and type the commands in the terminal, in this way, you will get used with the command line interface and OpenFOAM® commands.
- If you are already comfortable with OpenFOAM®, use the automatic scripts to run the cases.

Flow past a cylinder – From laminar to turbulent flow

What are we going to do?

- We will use this case to learn how to use different solvers and utilities.
- Remember, different solvers have different input dictionaries.
- We will learn how to convert the mesh from a third party software.
- We will learn how to use `setFields` to accelerate the convergence.
- We will learn how to map a solution from a coarse mesh to a fine mesh.
- We will learn how to setup a compressible solver.
- We will learn how to setup a turbulence case.
- We will use gnuplot to plot and compute the mean values of the lift and drag coefficients.
- We will visualize unsteady data.

Flow past a cylinder – From laminar to turbulent flow

Running the case

- Let us first convert the mesh from a third-party format (Fluent format).
- You will find this tutorial in the directory **`$PTOFC/101OF/vortex_shedding/c2`**
- In the terminal window type:

1. `$> foamCleanTutorials`
2. `$> fluent3DMeshToFoam ../../../meshes_and_geometries/vortex_shedding/ascii.msh`
3. `$> checkMesh`
4. `$> paraFoam`

- In step 2, we convert the mesh from Fluent format to OpenFOAM® format. Have in mind that the Fluent mesh must be in ascii format.
- If we try to open the mesh using `paraFoam` (step 4), it will crash. Can you tell what is the problem (read the screen)?

Flow past a cylinder – From laminar to turbulent flow

Running the case

- To avoid this problem, type in the terminal,

1. ```
   $> paraFoam -builtin
   ```

- Basically, the problem is related to the names and type of the patches in the file *boundary* and the boundary conditions (*U*, *p*). Notice that OpenFOAM® is telling you what and where is the error.

```
Created temporary 'c2.OpenFOAM'


--> FOAM FATAL IO ERROR:

    patch type 'patch' not constraint type 'empty'
    for patch front of field p in file "/home/joegi/my_cases_course/5x/101OF/vortex_shedding/c2/0/p"

file: /home/joegi/my_cases_course/5x/101OF/vortex_shedding/c2/0/p.boundaryField.front from line 60 to line 60.

    From function Foam::emptyFvPatchField<Type>::emptyFvPatchField(const Foam::fvPatch&, const
Foam::DimensionedField<Type, Foam::volMesh>&, const Foam::dictionary&) [with Type = double]
    in file fields/fvPatchFields/constraint/empty/emptyFvPatchField.C at line 80.

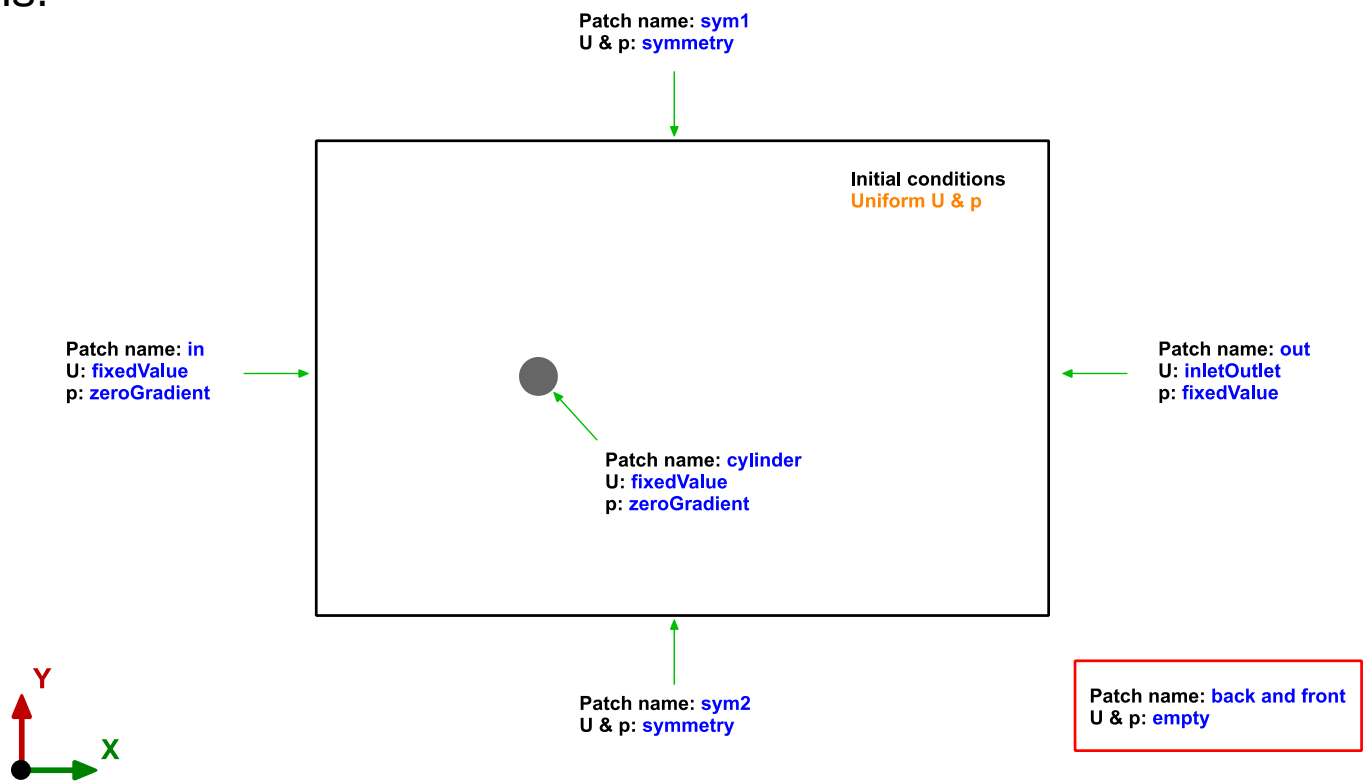
FOAM exiting
```

What

Where
```

Flow past a cylinder – From laminar to turbulent flow

- Remember, when converting meshes the **name** and **type** of the patches are not always set as you would like, so it is always a good idea to take a look at the file `boundary` and modify it according to your needs.
- Let us modify the `boundary` dictionary file.
- In this case, we would like to setup the following **numerical type** boundary conditions.



Flow past a cylinder – From laminar to turbulent flow

The *boundary* dictionary file

```
7
(
    out
    {
        type            patch;
        nFaces          80;
        startFace       18180;
    }
    sym1
    {
        type            symmetry;
        inGroups        1(symmetry);
        nFaces          100;
        startFace       18260;
    }
    sym2
    {
        type            symmetry;
        inGroups        1(symmetry);
        nFaces          100;
        startFace       18360;
    }
    in
    {
        type            patch;
        nFaces          80;
        startFace       18460;
    }
```

- This dictionary is located in the **`constant/polyMesh`** directory.
- This file is automatically created when converting or generating the mesh.
- To get a visual reference of the patches, you can the mesh with paraFoam/paraview.
- The type of the **out** patch is OK.
- The type of the **sym1** patch is OK.
- The type of the **sym2** patch is OK.
- The type of the **in** patch is OK.

Flow past a cylinder – From laminar to turbulent flow

The *boundary* dictionary file

```
46        cylinder
47        {
48            type            wall;
49            inGroups        1(wall);
50            nFaces          80;
51            startFace       18540;
52        }
53        back
54        {
55            type            patch;
56            nFaces          9200;
57            startFace       18620;
58        }
59        front
60        {
61            type            patch;
62            nFaces          9200;
63            startFace       27820;
64        }
65    )
```

- The type of the **cylinder** patch is OK.
- The type of the **back** patch is **NOT OK**. Remember, this is a 2D simulation, therefore the type should be **empty**.
- The type of the **front** patch is **NOT OK**. Remember, this is a 2D simulation, therefore the type should be **empty**.
- Remember, we assign the **numerical type** boundary conditions (numerical values), in the field files found in the directory *0*

Flow past a cylinder – From laminar to turbulent flow

- At this point, check that the **name** and **type** of the **base type** boundary conditions and **numerical type** boundary conditions are consistent. If everything is ok, we are ready to go.
- Do not forget to explore the rest of the dictionary files, namely:
  - *0/p* (**p** is defined as relative pressure)
  - *0/U*
  - constant/*transportProperties*
  - *system/controlDict*
  - *system/fvSchemes*
  - *system/fvSolution*
- Reminder:
  - The diameter of the cylinder is 2.0 m.
  - And we are targeting for a Re = 200.

$$\nu = \frac{\mu}{\rho} \qquad Re = \frac{\rho \times U \times D}{\mu} = \frac{U \times D}{\nu}$$

Flow past a cylinder – From laminar to turbulent flow

Running the case

- You will find this tutorial in the directory **`$PTOFC/101OF/vortex_shedding/c2`**
- In the folder **`c1`** you will find the same setup, but to generate the mesh we use `blockMesh` (the mesh is identical).
- To run this case, in the terminal window type:

1. `$> renumberMesh -overwrite`
2. `$> icoFoam | tee log.icofoam`
3. `$> pyFoamPlotWatcher.py log.icofoam`
   You will need to launch this script in a different terminal
4. `$> gnuplot scripts0/plot_coeffs`
   You will need to launch this script in a different terminal
5. `$> paraFoam`

Flow past a cylinder – From laminar to turbulent flow

Running the case

- In step 1 we use the utility `renumberMesh` to make the linear system more diagonal dominant, this will speed-up the linear solvers. This is inexpensive (even for large meshes), therefore is highly recommended to always do it.
- In step 2 we run the simulation and save the log file. Notice that we are sending the job to background.
- In step 3 we use `pyFoamPlotWatcher.py` to plot the residuals on-the-fly. As the job is running in background, we can launch this utility in the same terminal tab.
- In step 4 we use the gnuplot script `scripts0/plot_coeffs` to plot the force coefficients on-the-fly. Besides monitoring the residuals, is always a good idea to monitor a quantity of interest. Feel free to take a look at the script and to reuse it.
- The force coefficients are computed using **functionObjects**.
- After the simulation is over, we use `paraFoam` to visualize the results. Remember to use the VCR Controls to animate the solution.
- In the folder **`c1`** you will find the same setup, but to generate the mesh we use `blockMesh` (the mesh is identical).

Flow past a cylinder – From laminar to turbulent flow

- At this point try to use the following utilities. In the terminal type:
  - `$> postProcess -func vorticity -noZero`
    This utility will compute and write the vorticity field. The `–noZero` option means do not compute the vorticity field for the solution in the directory **`0`**. If you do not add the `-noZero` option, it will compute and write the vorticity field for all the saved solutions, including **`0`**
  - `$> postprocess -func 'grad(U)' -latestTime`
    This utility will compute and write the velocity gradient or `grad(U)` in the whole domain (including at the walls). The `-latestTime` option means compute the velocity gradient only for the last saved solution.
  - `$> postprocess -func 'grad(p)'`
    This utility will compute and write the pressure gradient or `grad(U)` in the whole domain (including at the walls).
  - `$> postProcess -func 'div(U)'`
    This utility will compute and write the divergence of the velocity field or `grad(U)` in the whole domain (including at the walls). You will need to add the keyword **div(U) Gauss linear**; in the dictionary `fvSchemes`.
  - `$> foamToVTK -time 50:300`
    This utility will convert the saved solution from OpenFOAM® format to VTK format. The `-time 50:300` option means convert the solution to VTK format only for the time directories **`50`** to **`300`**
  - `$> pisoFoam -postProcess -func CourantNo`
    This utility will compute and write the Courant number. This utility needs to access the solver database for the physical properties and additional quantities, therefore we need to tell what solver we are using. As the solver `icoFoam` does not accept the option `-postProcess`, we can use the solver `pisoFoam` instead. Remember, `icoFoam` is a fully laminar solver and `pisoFoam` is a laminar/turbulent solver.
  - `$> pisoFoam -postProcess -func wallShearStress`
    This utility will compute and write the wall shear stresses at the walls. As no arguments are given, it will save the wall shear stresses for all time steps.

Flow past a cylinder – From laminar to turbulent flow

Non-uniform field initialization

- In the previous case, it took about 150 seconds of simulation ime to onset the instability.
- If you are not interested in the initial transient or if you want to speed-up the computation, you can add a perturbation in order to trigger the onset of the instability.
- Let us use the utility `setFields` to initialize a non-uniform flow.
- This case is already setup in the directory

```
$PTOFC/101OF/vortex_shedding/c3
```

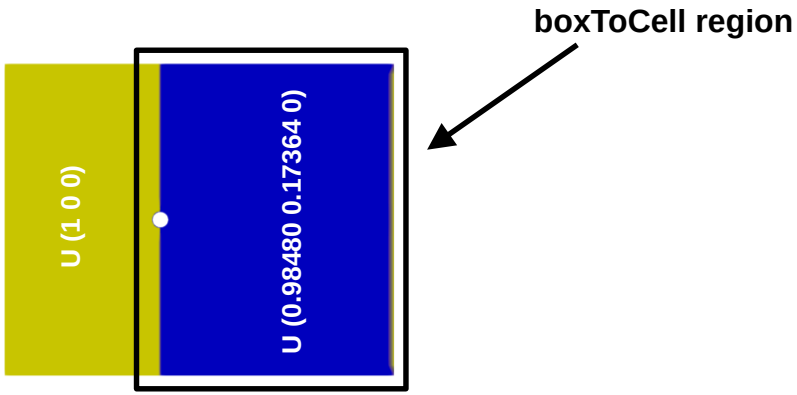
Flow past a cylinder – From laminar to turbulent flow

- Let us run the same case but using a non-uniform field

The `setFieldsDict` dictionary

```
17    defaultFieldValues
18    (
19        volVectorFieldValue U (1 0 0)
20    );
21
22    regions
23    (
24        boxToCell
25        {
26            box (0 -100 -100) (100 100 100);
27            fieldValues
28            (
29                volVectorFieldValue U (0.98480 0.17364 0)
30            );
31        }
32    );
```

- This dictionary file is located in the directory **system**.
- In lines 17-20 we set the default value of the velocity vector to be **(0 0 0)** in the whole domain.
- In lines 24-31, we initialize a rectangular region (**box**) just behind the cylinder with a velocity vector equal to **(0.98480 0.17364 0)**
- In this case, `setFields` will look for the dictionary file *U* and it will overwrite the original values according to the regions defined in `setFieldsDict`.



Flow past a cylinder – From laminar to turbulent flow

- Let us run the same case but using a non-uniform field.
- You will find this tutorial in the directory **`$PTOFC/101OF/vortex_shedding/c3`**
- Feel free to use the Fluent mesh or the mesh generated with `blockMesh`. Hereafter, we will use `blockMesh`.
- To run this case, in the terminal window type:

1. `$> foamCleanTutorials`
2. `$> blockMesh`
3. `$> rm -rf 0 > /dev/null 2>&1`
4. `$> cp -r 0_org/ 0`
5. `$> setFields`
6. `$> renumberMesh -overwrite`
7. `$> icoFoam | log.icofoam`
8. `$> pyFoamPlotWatcher.py log.icofoam`
   You will need to launch this script in a different terminal
9. `$> gnuplot scripts0/plot_coeffs`
   You will need to launch this script in a different terminal
10. `$> paraFoam`

Flow past a cylinder – From laminar to turbulent flow

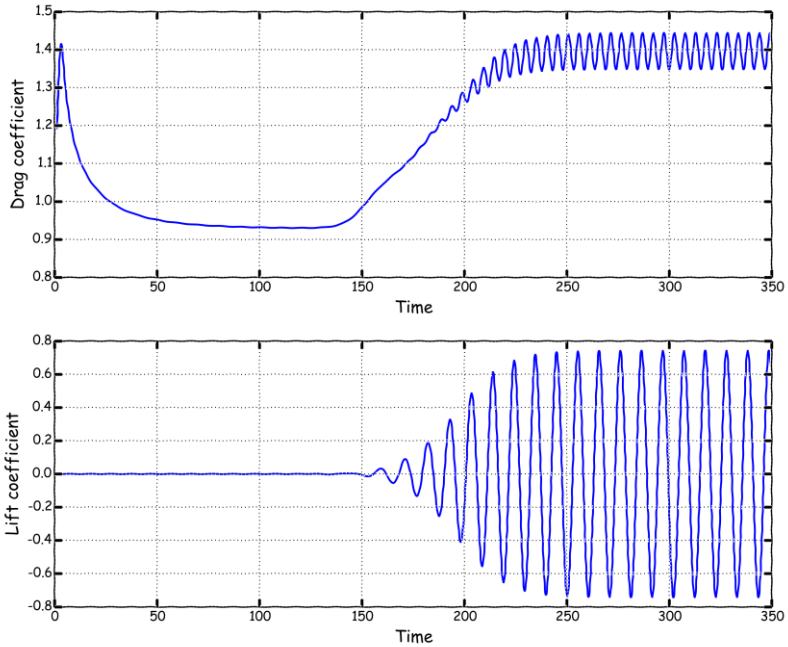
Running the case – Non-uniform field initialization

- In step 2 we generate the mesh using `blockMesh`. The **name** and **type** of the patches are already set in the dictionary `blockMeshDict` so there is no need to modify the `boundary` file.
- In step 4 we copy the original files to the directory `0`. We do this to keep a backup of the original files as the file *`0/U`* will be overwritten when using `setFields`.
- In step 5 we initialize the solution using `setFields`.
- In step 6 we use the utility `renumberMesh` to make the linear system more diagonal dominant, this will speed-up the linear solvers.
- In step 7 we run the simulation and save the log file. Notice that we are sending the job to background.
- In step 8 we use `pyFoamPlotWatcher.py` to plot the residuals on-the-fly. As the job is running in background, we can launch this utility in the same terminal tab.
- In step 9 we use the gnuplot script `scripts0/plot_coeffs` to plot the lift and drag coefficients on-the-fly. Besides monitoring the residuals, is always a good idea to monitor a quantity of interest. Feel free to take a look at the script and to reuse it.

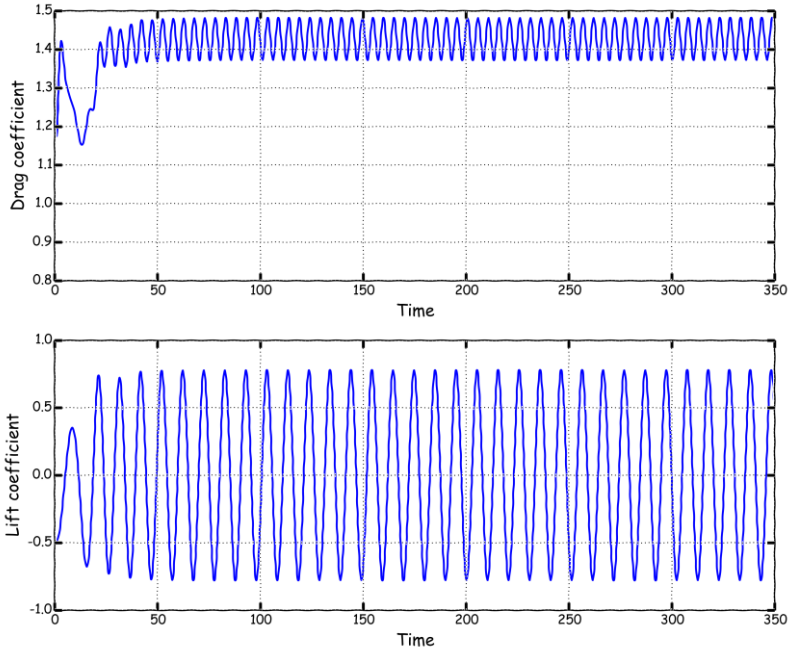
Flow past a cylinder – From laminar to turbulent flow

Does non-uniform field initialization make a difference?

- A picture is worth a thousand words. No need to tell you yes, even if the solutions are slightly different.
- This bring us to the next subject, for how long should we run the simulation?



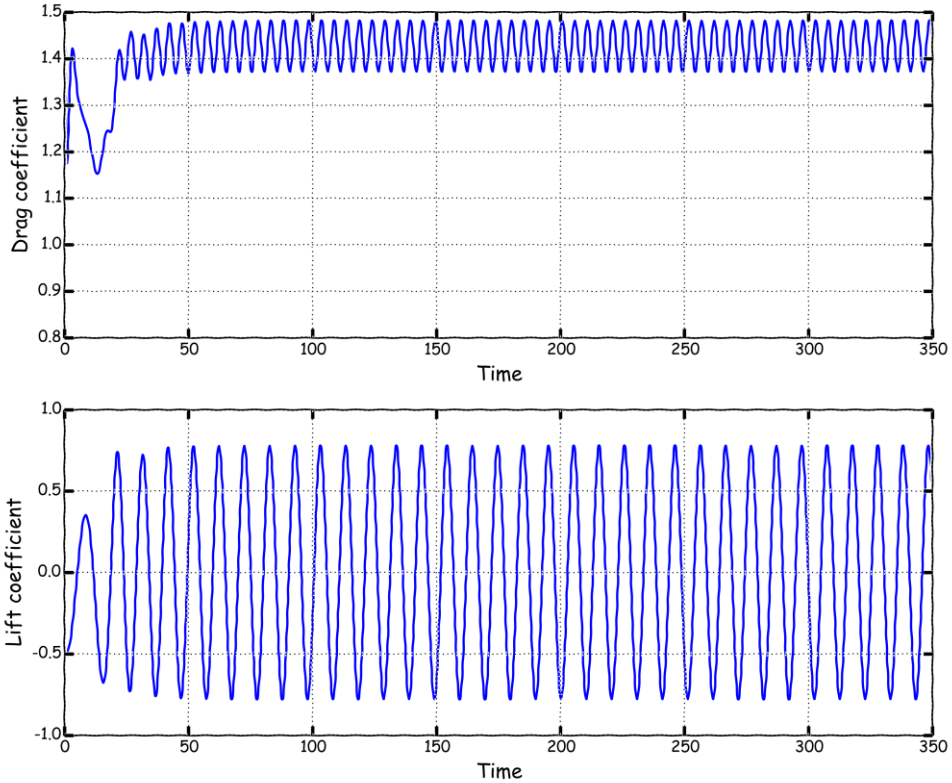
No field initialization



With field initialization

Flow past a cylinder – From laminar to turbulent flow

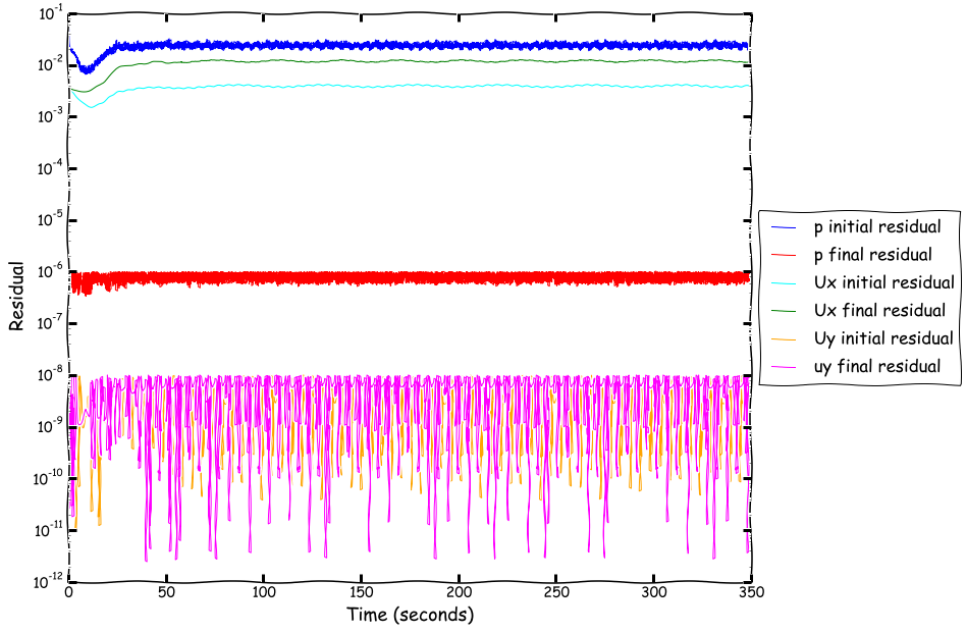
For how long should run the simulation?



- This is the difficult part when dealing with unsteady flows.
- Usually you run the simulation until the behavior of a quantity of interest does not oscillates or it becomes periodic.
- In this case we can say that after the 50 seconds mark the solution becomes periodic, therefore there is no need to run up to 350 seconds (unless you want to gather a lot of statistics).
- We can stop the simulation at 150 seconds (or maybe less), and do the average of the quantities between 100 and 150 seconds.

Flow past a cylinder – From laminar to turbulent flow

What about the residuals?



- Residuals are telling you a lot, but they are difficult to interpret.
- In this case the fact that the initial residuals are increasing after about 10 seconds, does not mean that the solution is diverging. This is in indication that something is happening (in this case the onset of the instability).
- Remember, the residuals should always drop to the tolerance criteria set in the `fvSolution` dictionary (final residuals). If they do not drop to the desired tolerance, we are talking about unconverged time-steps.
- Things that are not clear from the residuals:
  - For how long should we run the simulation?
  - Is the solution converging to the right value?

Flow past a cylinder – From laminar to turbulent flow

How to compute force coefficients

```
68      functions
69      {

195         forceCoeffs_object
196         {
205             type forceCoeffs;
206             functionObjectLibs ("libforces.so");
208             patches (cylinder);
209
210             pName p;
211             Uname U;
212             rhoName rhoInf;
213             rhoInf 1.0;
214
215             //// Dump to file
216             log true;
217
218             CofR (0.0 0 0);
219             liftDir (0 1 0);
220             dragDir (1 0 0);
221             pitchAxis (0 0 1);
222             magUInf 1.0;
223             lRef 1.0;
224             Aref 2.0;
225
226             outputControl   timeStep;
227             outputInterval  1;
228         }

255     };
```

- To compute the force coefficients we use **functionObjects**.
- Remember, **functionObjects** are defined at the end of the *controlDict* dictionary file.
- In line 195 we give a name to the **functionObject**.
- In line 208 we define the patch where we want to compute the forces.
- In lines 212-213 we define the reference density value.
- In line 218 we define the center of rotation (for moments).
- In line 219 we define the lift force axis.
- In line 220 we define the drag force axis.
- In line 221 we define the axis of rotation for moment computation.
- In line 223 we give the reference length (for computing the moments)
- In line 224 we give the reference area (in this case the frontal area).
- The output of this **functionObject** is saved in the file *forceCoeffs.dat* located in the directory **forceCoeffs_object/0/**

Flow past a cylinder – From laminar to turbulent flow

Can we compute basic statistics of the force coefficients using gnuplot?

- Yes we can. Enter the gnuplot prompt and type:

1. `gnuplot> stats 'postProcessing/forceCoeffs_object/0/forceCoeffs.dat' u 3`
   This will compute the basic statistics of all the rows in the file forceCoeffs.dat (we are sampling column 3 in the input file)

2. `gnuplot> stats 'postProcessing/forceCoeffs_object/0/forceCoeffs.dat' every ::3000::7000 u 3`
   This will compute the basic statistics of rows 3000 to 7000 in the file forceCoeffs.dat (we are sampling column 3 in the input file)

3. `gnuplot> plot 'postProcessing/forceCoeffs_object/0/forceCoeffs.dat' u 3 w l`
   This will plot column 3 against the row number (iteration number)

4. `gnuplot> exit`
   To exit gnuplot

- Remember the force coefficients information is saved in the file `forceCoeffs.dat` located in the directory **`postProcessing/forceCoeffs_object/0`**

Flow past a cylinder – From laminar to turbulent flow

On the solution accuracy

```
17    ddtSchemes
18    {
20      default         backward;
22    }
23
24    gradSchemes
25    {
31        default           cellLimited leastSquares 1;
37    }
38
39    divSchemes
40    {
41        default         none;
45        div(phi,U)      Gauss linearUpwindV default;
49    }
50
51    laplacianSchemes
52    {
59        default         Gauss linear limited 1;
60    }
61
62    interpolationSchemes
63    {
64        default         linear;
66    }
67
68    snGradSchemes
69    {
71        default         limited 1;
72    }
```

- At the end of the day we want a solution that is second order accurate.
- We define the discretization schemes (and therefore the accuracy) in the dictionary *`fvSchemes`*.
- In this case, for time discretization (**ddtSchemes**) we are using the **backward** method.
- For gradient discretization (**gradSchemes**) we are using the **leastSquares** method with slope limiters (**cellLimited**).
- For the discretization of the convective terms (**divSchemes**) we are using **linearUpwindV** interpolation method for the term **div(rho,U)**.
- For the discretization of the Laplacian (**laplacianSchemes** and **snGradSchemes**) we are using the **Gauss linear limited 1** method
- This method is second order accurate.

Flow past a cylinder – From laminar to turbulent flow

On the solution tolerance and linear solvers

```
17    solvers
18    {
31        p
32        {
33            solver           GAMG;
34            tolerance        1e-6;
35            relTol           0;
36            smoother         GaussSeidel;
37            nPreSweeps       0;
38            nPostSweeps      2;
39            cacheAgglomeration on;
40            agglomerator     faceAreaPair;
41            nCellsInCoarsestLevel 100;
42            mergeLevels      1;
43        }
44
45        pFinal
46        {
47            $p;
48            relTol          0;
49        }
50
51        U
52        {
53            solver          PBiCG;
54            preconditioner  DILU;
55            tolerance       1e-08;
56            relTol          0;
57        }
69    }
70
71    PISO
72    {
73        nCorrectors     2;
74        nNonOrthogonalCorrectors 2;
77    }
```

- We define the solution tolerance and linear solvers in the dictionary *fvSolution*.
- To solve the pressure (**p**) we are using the **GAMG** method with an absolute **tolerance** of 1e-6 and a relative tolerance **relTol** of 0.01.
- The entry **pFinal** refers to the final correction of the **PISO** loop. It is possible to use a tighter convergence criteria only in the last iteration.
- To solve **U** we are using the solver **PBiCG** and the **DILU** preconditioner**,** with an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0 (the solver will stop iterating when it meets any of the conditions).
- Solving for the velocity is relative inexpensive, whereas solving for the pressure is expensive.
- The **PISO** sub-dictionary contains entries related to the pressure-velocity coupling (in this case the **PISO** method). Hereafter we are doing two **PISO** correctors (**nCorrectors**) and two non-orthogonal corrections (**nNonOrthogonalCorrectors**).

Flow past a cylinder – From laminar to turbulent flow

On the runtime parameters

```
application     icoFoam;

startFrom       latestTime;

startTime       0;

stopAt          endTime;

endTime         350;

deltaT          0.05;

writeControl    runTime;

writeInterval   1;

purgeWrite      0;

writeFormat     ascii;

writePrecision  8;

writeCompression off;

timeFormat      general;

timePrecision   6;

runTimeModifiable true;
```

- This case starts from the latest saved solution (**startFrom**).
- In this case as there are no saved solutions, it will start from 0 (**startTime**).
- It will run up to 350 seconds (**endTime**).
- The time step of the simulation is 0.05 seconds (**deltaT**). The time step has been chosen in such a way that the Courant number is less than 1
- It will write the solution every 1 second (**writeInterval**) of simulation time (**runTime**).
- It will keep all the solution directories (**purgeWrite**).
- It will save the solution in ascii format (**writeFormat**).
- The write precision is 8 digits (**writePrecision**).
- And as the option **runTimeModifiable** is on, we can modify all these entries while we are running the simulation.

Flow past a cylinder – From laminar to turbulent flow

The output screen

- This is the output screen of the `icoFoam` solver.

```
Time = 350

Courant Number mean: 0.11299953 max: 0.87674198
DILUPBiCG:  Solving for Ux, Initial residual = 0.0037946307, Final residual = 4.8324843e-09, No Iterations 3
DILUPBiCG:  Solving for Uy, Initial residual = 0.011990022, Final residual = 5.8815028e-09, No Iterations 3
GAMG:  Solving for p, Initial residual = 0.022175872, Final residual = 6.2680545e-07, No Iterations 14
GAMG:  Solving for p, Initial residual = 0.0033723932, Final residual = 5.8494331e-07, No Iterations 8
GAMG:  Solving for p, Initial residual = 0.0010074964, Final residual = 4.4726195e-07, No Iterations 7
time step continuity errors : sum local = 1.9569266e-11, global = -3.471923e-14, cumulative = -2.8708402e-10
GAMG:  Solving for p, Initial residual = 0.0023505548, Final residual = 9.9222424e-07, No Iterations 8
GAMG:  Solving for p, Initial residual = 0.00045248026, Final residual = 7.7250386e-07, No Iterations 6
GAMG:  Solving for p, Initial residual = 0.00014664077, Final residual = 4.5825218e-07, No Iterations 5
time step continuity errors : sum local = 2.0062733e-11, global = 1.2592813e-13, cumulative = -2.8695809e-10
ExecutionTime = 746.46 s  ClockTime = 807 s

faceSource inMassFlow output:
    sum(in) of phi = -40

faceSource outMassFlow output:
    sum(out) of phi = 40

fieldAverage fieldAverage output:
    Calculating averages

    Writing average fields

forceCoeffs forceCoeffs_object output:
    Cm    = 0.0043956828
    Cd    = 1.4391786
    Cl    = 0.44532594
    Cl(f) = 0.22705865
    Cl(r) = 0.21826729

fieldMinMax minmaxdomain output:
    min(p) = -0.82758125 at location (2.2845502 0.27072681 1.4608125e-17)
    max(p) = 0.55952746 at location (-1.033408 -0.040619346 0)
    min(U) = (-0.32263726 -0.054404584 -1.8727033e-19) at location (2.4478235 -0.69065656 -2.5551406e-17)
    max(U) = (1.4610304 0.10220218 2.199981e-19) at location (0.43121241 1.5285504 -1.4453535e-17)
```

Courant number

nCorrector 1

nNonOrthogonalCorrectors 2

pFinal

nCorrector 2

Mass flow at in patch

Mass flow at out patch

Computing averages of fields

nCorrectors 2

Force coefficients

Min and max values

Flow past a cylinder – From laminar to turbulent flow

Let us use a potential solver to find a quick solution

- In this case we are going to use the potential solver `potentialFoam` (remember potential solvers are inviscid, irrotational and incompressible)
- This solver is super fast and it can be used to find a solution to be used as initial conditions (non-uniform field) for an incompressible solver.
- A good initial condition will accelerate and improve the convergence rate.
- This case is already setup in the directory

```
$PTOFC/101OF/vortex_shedding/c4
```

- Do not forget to explore the dictionary files.
- The following dictionaries are different
    - *`system/fvSchemes`*
    - *`system/fvSolution`*

Try to spot the differences.

Flow past a cylinder – From laminar to turbulent flow

Running the case – Let us use a potential solver to find a quick solution

- You will find this tutorial in the directory **`$PTOFC/101OF/vortex_shedding/c4`**
- Feel free to use the Fluent mesh or the mesh generated with `blockMesh`. In this case we will use `blockMesh`.
- To run this case, in the terminal window type:

1. `$> foamCleanTutorials`
2. `$> blockMesh`
3. `$> rm -rf 0`
4. `$> cp -r 0_org 0`
5. `$> potentialFoam -noFunctionObjects -initialiseUBCs -writep -writePhi`
6. `$> paraFoam`

Flow past a cylinder – From laminar to turbulent flow

Running the case – Let us use a potential solver to find a quick solution

- In step 2 we generate the mesh using `blockMesh`. The **name** and **type** of the patches are already set in the dictionary `blockMeshDict` so there is no need to modify the *`boundary`* file.
- In step 4 we copy the original files to the directory **`0`**. We do this to keep a backup of the original files as they will be overwritten by the solver `potentialFoam`.
- In step 5 we run the solver. We use the option `-noFunctionObjects` to avoid conflicts with the **functionobjects**. The options `-writep` and `-writePhi` will write the pressure field and fluxes respectively.
- At this point, if you want to use this solution as initial conditions for an incompressible solver, just copy the files *`U`* and *`p`* into the start directory of the incompressible case you are looking to run. Have in mind that the meshes need to be the same.
- Be careful with the **name** and **type** of the boundary conditions, they should be same between the potential case and incompressible case.

Flow past a cylinder – From laminar to turbulent flow

Potential solution

- Using a potential solution as initial conditions is much better than using a uniform flow. It will speed up the solution and it will give you more stability.
- Finding a solution using the potential solver is inexpensive.

Velocity field

Pressure field

Flow past a cylinder – From laminar to turbulent flow

The output screen

- This is the output screen of the `potentialFoam` solver.
- The output of this solver is also a good indication of the sensitivity of the mesh quality to gradients computation. If you see that the number of iterations are dropping iteration after iteration, it means that the mesh is fine.
- If the number of iterations remain stalled, it means that the mesh is sensitive to gradients, so should use non-orthogonal correction.
- In this case we have a good mesh.

```
Calculating potential flow
DICPCG:  Solving for Phi, Initial residual = 2.6622265e-05, Final residual = 8.4894837e-07, No Iterations 27
DICPCG:  Solving for Phi, Initial residual = 1.016986e-05, Final residual = 9.5168103e-07, No Iterations 9
DICPCG:  Solving for Phi, Initial residual = 4.0789046e-06, Final residual = 7.7788216e-07, No Iterations 5
DICPCG:  Solving for Phi, Initial residual = 1.8251249e-06, Final residual = 8.8483568e-07, No Iterations 1
DICPCG:  Solving for Phi, Initial residual = 1.1220074e-06, Final residual = 5.6696809e-07, No Iterations 1
DICPCG:  Solving for Phi, Initial residual = 7.1187246e-07, Final residual = 7.1187246e-07, No Iterations 0
Continuity error = 1.3827583e-06
Interpolated velocity error = 7.620206e-07

Calculating approximate pressure field
DICPCG:  Solving for p, Initial residual = 0.0036907012, Final residual = 9.7025397e-07, No Iterations 89
DICPCG:  Solving for p, Initial residual = 0.0007470416, Final residual = 9.9942495e-07, No Iterations 85
DICPCG:  Solving for p, Initial residual = 0.00022829496, Final residual = 8.6107759e-07, No Iterations 36
DICPCG:  Solving for p, Initial residual = 7.9622793e-05, Final residual = 8.4360883e-07, No Iterations 31
DICPCG:  Solving for p, Initial residual = 2.8883108e-05, Final residual = 8.7152873e-07, No Iterations 25
DICPCG:  Solving for p, Initial residual = 1.151539e-05, Final residual = 9.7057871e-07, No Iterations 9
ExecutionTime = 0.17 s  ClockTime = 0 s

End
```

Velocity computation

Initial approximation

nNonOrthogonalCorrectors 5

Pressure computation

Flow past a cylinder – From laminar to turbulent flow

Let us map a solution from a coarse mesh to a finer mesh

- It is also possible to map the solution from a coarse mesh to a finer mesh (and all the way around).
- For instance, you can compute a full Navier Stokes solution in a coarse mesh (fast solution), and then map it to a finer mesh.
- Let us map the solution from the potential solver to a finer mesh (if you want you can map the solution obtained using `icoFoam`). To do this we will use the utility `mapFields`.
- This case is already setup in the directory

```
$PTOFC/101OF/vortex_shedding/c6
```

Flow past a cylinder – From laminar to turbulent flow

Running the case – Let us map a solution from a coarse mesh to a finer mesh

- You will find this tutorial in the directory **`$PTOFC/101OF/vortex_shedding/c6`**
- To generate the mesh, use `blockMesh` (remember this mesh is finer).
- To run this case, in the terminal window type:

1. `$> foamCleanTutorials`
2. `$> blockMesh`
3. `$> rm -rf 0`
4. `$> cp -r 0_org 0`
5. `$> mapfields ../c4 -consistent -noFunctionObjects -mapMethod cellPointInterpolate -sourceTime 0`
6. `$> paraFoam`

Flow past a cylinder – From laminar to turbulent flow

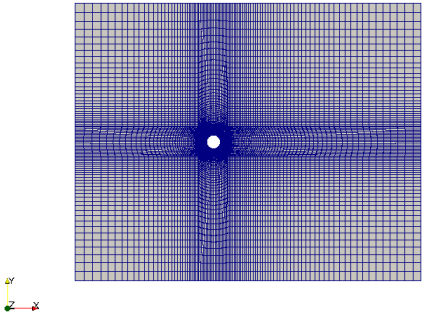
Running the case – Let us map a solution from a coarse mesh to a finer mesh

- In step 2 we generate a finer mesh using `blockMesh`. The **name** and **type** of the patches are already set in the dictionary `blockMeshDict` so there is no need to modify the `boundary` file.
- In step 4 we copy the original files to the directory `0`. We do this to keep a backup of the original files as they will be overwritten by the utility `mapFields`.
- In step 5 we use the utility `mapFields` with the following options:
  - We copy the solution from the directory `../c4`
  - The options `-consistent` is used when the domains and BCs are the same.
  - The option `-noFunctionObjects` is used to avoid conflicts with the **functionObjects**.
  - The option `-mapMethod cellPointInterpolate` defines the interpolation method.
  - The option `-sourceTime 0` defines the time from which we want to interpolate the solution.

Flow past a cylinder – From laminar to turbulent flow

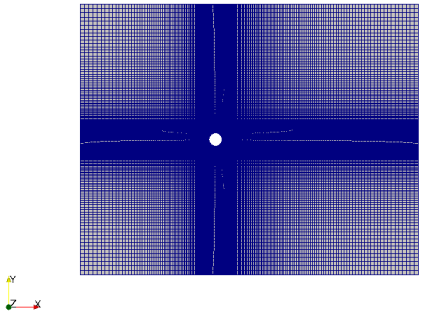
The meshes and the mapped fields

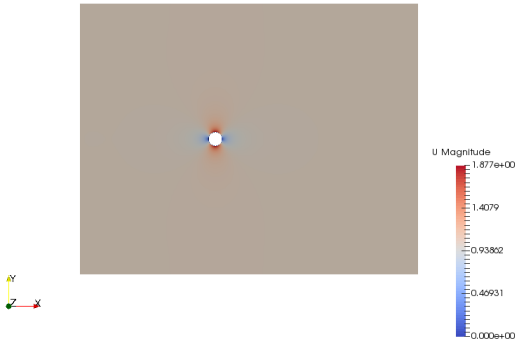
Coarse mesh



`mapFields`

Fine mesh





Flow past a cylinder – From laminar to turbulent flow

The output screen

- This is the output screen of the `mapFields` utility.
- The utility `mapFields`, will try to interpolate all fields in the source directory.
- You can control the target time via the **startFrom** and **startTime** keywords in the *`controlDict`* dictionary file.

```
Source: ".." "c4"                                                  Source case
Target: "/home/joegi/my_cases_course/5x/101OF/vortex_shedding" "c6"   Target case
Mapping method: cellPointInterpolate                               Interpolation method

Create databases as time

Source time: 0                                                     Source time
Target time: 0                                                     Target time
Create meshes

Source mesh size: 9200  Target mesh size: 36800                    Source and target mesh cell count


Consistently creating and mapping fields for time 0

    interpolating Phi
    interpolating p                                                Interpolated fields
    interpolating U

End
```

Flow past a cylinder – From laminar to turbulent flow

Setting a turbulent case

- So far we have used laminar incompressible solvers.
- Let us do a turbulent simulation.
- When doing turbulent simulations, we need to choose the turbulence model, define the boundary and initial conditions for the turbulent quantities, and modify the `fvSchemes` and `fvSolution` dictionaries to take account for the new variables we are solving (the transported turbulent quantities).
- This case is already setup in the directory

```
$PTOFC/101OF/vortex_shedding/c14
```

Flow past a cylinder – From laminar to turbulent flow

- The following dictionaries remain unchanged
  - *system/blockMeshDict*
  - *constant/polyMesh/boundary*
  - *0/p*
  - *0/U*

- The following dictionaries need to be adapted for the turbulence case
  - *constant/transportProperties*
  - *system/controlDict*
  - *system/fvSchemes*
  - *system/fvSolution*

- The following dictionaries need to be adapted for the turbulence case
  - *constant/turbulenceProperties*

Flow past a cylinder – From laminar to turbulent flow

The *transportProperties* dictionary file

- This dictionary file is located in the directory **constant**.
- In this file we set the transport model and the kinematic viscosity (**nu**).

```
16    transportModel  Newtonian;
17
19    nu              nu [ 0 2 -1 0 0 0 0 ] 0.0002;
```

- Reminder:
  - The diameter of the cylinder is 2.0 m.
  - And we are targeting for a Re = 10000.

$$\nu = \frac{\mu}{\rho} \qquad Re = \frac{\rho \times U \times D}{\mu} = \frac{U \times D}{\nu}$$

Flow past a cylinder – From laminar to turbulent flow

The `turbulenceProperties` dictionary file

- This dictionary file is located in the directory **`constant`**.
- In this dictionary file we select what model we would like to use (laminar or turbulent).
- In this case we are interested in modeling turbulence, therefore the dictionary is as follows

```
simulationType  RAS;

RAS
{
    RASModel        kOmegaSST;

    turbulence      on;

    printCoeffs     on;
}
```

RANS type simulation

RANS sub-dictionary

RANS model to use

Turn on/off turbulence. Runtime modifiable

Print coefficients at the beginning

- If you want to know the models available use the banana method.

Flow past a cylinder – From laminar to turbulent flow

The `controlDict` dictionary

```
17    application     pimpleFoam;
18
20    startFrom       latestTime;
21
22    startTime       0;
23
24    stopAt          endTime;
25
26    endTime         500;
27
28    deltaT          0.001;
32
33    writeControl    runTime;
41
42    writeInterval   1;
43
50    purgeWrite      0;
51
52    writeFormat     ascii;
53
54    writePrecision  8;
55
56    writeCompression off;
57
58    timeFormat      general;
59
60    timePrecision   6;
61
62    runTimeModifiable yes;
63
64    adjustTimeStep  yes;
65
66    maxCo           0.9;
67    maxDeltaT       0.1;
```

- This case will start from the last saved solution (**startFrom**). If there is no solution, the case will start from time 0 (**startTime**).
- It will run up to 500 seconds (**endTime**).
- The initial time step of the simulation is 0.001 seconds (**deltaT**).
- It will write the solution every 1 second (**writeInterval**) of simulation time (**runTime**).
- It will keep all the solution directories (**purgeWrite**).
- It will save the solution in ascii format (**writeFormat**).
- The write precision is 8 digits (**writePrecision**).
- And as the option **runTimeModifiable** is on, we can modify all these entries while we are running the simulation.
- In line 64 we turn on the option **adjustTimeStep**. This option will automatically adjust the time step to achieve the maximum desired courant number **maxCo** (line 66).
- We also set a maximum time step **maxDeltaT** in line 67.
- Remember, the first time step of the simulation is done using the value set in line 28 and then it is automatically scaled to achieve the desired maximum values (lines 66-67).
- The feature **adjustTimeStep** is only present in the **PIMPLE** family solvers, but it can be added to any solver by modifying the source code.

Flow past a cylinder – From laminar to turbulent flow

The *fvSchemes* dictionary

```
17    ddtSchemes
18    {
21        default         CrankNicolson 0.5;
22    }
24    gradSchemes
25    {
31        default           cellLimited leastSquares 1;
36        grad(U)           cellLimited Gauss linear 1;
37    }
39    divSchemes
40    {
41        default         none;
47        div(phi,U)      Gauss linearUpwindV grad(U);
49        div((nuEff*dev2(T(grad(U))))) Gauss linear;
51        div(phi,k)          Gauss linearUpwind default;
52        div(phi,omega)      Gauss linearUpwind default;
63    }
65    laplacianSchemes
66    {
74         default         Gauss linear limited 1;
75    }
77    interpolationSchemes
78    {
79        default         linear;
81    }
83    snGradSchemes
84    {
86        default         limited 1;
87    }
89    wallDist
90    {
91        method meshWave;
92    }
```

- In this case, for time discretization (**ddtSchemes**) we are using the blended **CrankNicolson** method. The blending coefficient goes from 0 to 1, where 0 is equivalent to the **Euler** method and 1 is a pure **Crank Nicolson**.
- For gradient discretization (**gradSchemes**) we are using as default option the **leastSquares** method. For **grad(U)** we are using **Gauss linear** with slope limiters (**cellLimited**). You can define different methods for every term in the governing equations, for example, you can define a different method for **grad(p)**.
- For the discretization of the convective terms (**divSchemes**) we are using **linearUpwindV** interpolation method with slope limiters for the term **div(phi,U)**.
- For the terms **div(phi,k)** and **div(phi,omega)** we are using **linearUpwind** interpolation method with no slope limiters. These terms are related to the turbulence modeling.
- For the term **div((nuEff*dev2(T(grad(U)))))** we are using **linear** interpolation (this term is related to turbulence modeling).
- For the discretization of the Laplacian (**laplacianSchemes** and **snGradSchemes**) we are using the **Gauss linear limited 1** method.
- To compute the distance to the wall and normals to the wall, we use the method **meshWave**. This only applies when using wall functions (turbulence modeling).
- This method is second order accurate.

Flow past a cylinder – From laminar to turbulent flow

The *fvSolution* dictionary

```
17      solvers
18      {
31          p
32          {
33              solver           GAMG;
34              tolerance        1e-6;
35              relTol           0.001;
36              smoother         GaussSeidel;
37              nPreSweeps       0;
38              nPostSweeps      2;
39              cacheAgglomeration on;
40              agglomerator     faceAreaPair;
41              nCellsInCoarsestLevel 100;
42              mergeLevels      1;
44              minIter        2;
45          }
46
47          pFinal
48          {
49              solver          PCG;
50              preconditioner  DIC;
51              tolerance       1e-06;
52              relTol          0;
54              minIter        3;
55          }
56
57          U
58          {
59              solver          PBiCGStab;
60              preconditioner  DILU;
61              tolerance       1e-08;
62              relTol          0;
63              minIter        3;
64          }
```

- To solve the pressure (**p**) we are using the **GAMG** method, with an absolute **tolerance** of 1e-6 and a relative tolerance **relTol** of 0.001. Notice that we are fixing the number of minimum iterations (**minIter**).
- To solve the final pressure correction (**pFinal**) we are using the **PCG** method with the **DIC** preconditioner, with an absolute **tolerance** of 1e-6 and a relative tolerance **relTol** of 0.
- Notice that we can use different methods between **p** and **pFinal**. In this case we are using a tighter tolerance for the last iteration.
- We are also fixing the number of minimum iterations (**minIter**). This entry is optional.
- To solve **U** we are using the solver **PBiCGStab** with the **DILU** preconditioner, an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0. Notice that we are fixing the number of minimum iterations (**minIter**).

Flow past a cylinder – From laminar to turbulent flow

The *fvSolution* dictionary

```
17      solvers
18      {
77          UFinal
78          {
79              solver          PBiCGStab;
80              preconditioner  DILU;
81              tolerance       1e-08;
82              relTol          0;
83              minIter          3;
84          }
85
86          omega
87          {
88              solver          PBiCGStab;
89              preconditioner  DILU;
90              tolerance       1e-08;
91              relTol          0;
92              minIter          3;
93          }
94
95          omegaFinal
96          {
97              solver          PBiCGStab;
98              preconditioner  DILU;
99              tolerance       1e-08;
100             relTol          0;
101             minIter          3;
102         }
103
104         k
105         {
106             solver          PBiCGStab;
107             preconditioner  DILU;
108             tolerance       1e-08;
109             relTol          0;
110             minIter          3;
111         }
```

- To solve **UFinal** we are using the solver **PBiCGStab** with an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0. Notice that we are fixing the number of minimum iterations (**minIter**).
- To solve **omega** and **omegaFinal** we are using the solver **PBiCGStab** with an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0. Notice that we are fixing the number of minimum iterations (**minIter**).
- To solve **k** we are using the solver **PBiCGStab** with an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0. Notice that we are fixing the number of minimum iterations (**minIter**).

Flow past a cylinder – From laminar to turbulent flow

The *fvSolution* dictionary

```
113         kFinal
114         {
115             solver          PBiCGStab;
116             preconditioner  DILU;
117             tolerance       1e-08;
118             relTol          0;
119             minIter          3;
120         }
121     }
122
123     PIMPLE
124     {
126             nOuterCorrectors 1;
127             //nOuterCorrectors 2;
128
129             nCorrectors 3;
130             nNonOrthogonalCorrectors 1;
133     }
134
135     relaxationFactors
136     {
137         fields
138         {
139             p               0.3;
140         }
141         equations
142         {
143             U               0.7;
144             k               0.7;
145             omega           0.7;
146         }
147     }
```

- To solve **kFinal** we are using the solver **PBiCGStab** with an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0. Notice that we are fixing the number of minimum iterations (**minIter**).
- In lines 123-133 we setup the entries related to the pressure-velocity coupling method used (**PIMPLE** in this case). Setting the keyword **nOuterCorrectors** to 1 is equivalent to running using the **PISO** method.
- To gain more stability we are using 1 outer correctors (**nOuterCorrectors**), 3 inner correctors or **PISO** correctors (**nCorrectors**), and 1 correction due to non-orthogonality (**nNonOrthogonalCorrectors**).
- Remember, adding corrections increase the computational cost.
- In lines 135-147 we setup the under relaxation factors used during the outer corrections (pseudo transient iterations). If you are working in **PISO** mode (only one outer correction or **nOuterCorrectors**), these values are ignored.

Flow past a cylinder – From laminar to turbulent flow

- The following dictionaries are new
    - `0/k`
    - `0/omega`
    - `0/nut`

  These are the field variables related to the closure equations of the turbulent model.

- As we are going to use the $\kappa - \omega\ SST$ model we need to define the initial conditions and boundaries conditions.
- To define the IC/BC we will use the free stream values of κ and ω
- In the following site, you can find a lot information abut choosing initial and boundary conditions for the different turbulence models:
    - https://turbmodels.larc.nasa.gov/

Flow past a cylinder – From laminar to turbulent flow

$\kappa - \omega\ SST$ Turbulence model free-stream boundary conditions

- The initial value for the turbulent kinetic energy κ can be found as follows

$$\kappa = \frac{3}{2}(UI)^2$$

- The initial value for the specific kinetic energy ω can be found as follows

$$\omega = \frac{\rho\kappa}{\mu}\frac{\mu_t}{\mu}^{-1}$$

- Where $\frac{\mu_t}{\mu}$ is the viscosity ratio and $I = \frac{u'}{\bar{u}}$ is the turbulence intensity.

- If you are working with external aerodynamics or virtual wind tunnels, you can use the following reference values for the turbulence intensity and the viscosity ratio. They work most of the times, but it is a good idea to have some experimental data or a better initial estimate.

	Low	Medium	High
I	1.0 %	5.0 %	10.0 %
μ_t/μ	1	10	100

Flow past a cylinder – From laminar to turbulent flow

The file *0/k*

```
19    internalField   uniform 0.00015;
20
21    boundaryField
22    {
23        out
24        {
25            type            inletOutlet;
26            inletValue      uniform 0.00015;
27            value           uniform 0.00015;
28        }
29        sym1
30        {
31            type            symmetryPlane;
32        }
33        sym2
34        {
35            type            symmetryPlane;
36        }
37        in
38        {
39            type            fixedValue;
40            value           uniform 0.00015;
41        }
42        cylinder
43        {
44            type            kqRWallFunction;
45            value           uniform 0.00015;
46        }
47        back
48        {
49            type            empty;
50        }
51        front
52        {
53            type            empty;
54        }
55    }
```

- We are using uniform initial conditions (line 19).
- For the **in** patch we are using a **fixedValue** boundary condition.
- For the **out** patch we are using an **inletOutlet** boundary condition (this boundary condition avoids backflow).
- For the **cylinder** patch (which is **base type wall**), we are using the **kqRWallFunction** boundary condition. This is a wall function, we are going to talk about this when we deal with turbulence modeling. Remember, we can use wall functions only if the patch is of **base type wall**.
- The rest of the patches are constrained.
- FYI, the inlet velocity is 1 and the turbulence intensity is equal to 1%.

Flow past a cylinder – From laminar to turbulent flow

The file *0/omega*

```
19    internalField   uniform 0.075;
20
21    boundaryField
22    {
23        out
24        {
25            type            inletOutlet;
26            inletValue      uniform 0.075;
27            value           uniform 0.075;
28        }
29        sym1
30        {
31            type            symmetryPlane;
32        }
33        sym2
34        {
35            type            symmetryPlane;
36        }
37        in
38        {
39            type            fixedValue;
40            value           uniform 0.075;
41        }
42        cylinder
43        {
44            type            omegaWallFunction;
45            Cmu             0.09;
46            kappa           0.41;
47            E               9.8;
48            beta1           0.075;
49            value           uniform 0.075;
50        }
51        back
52        {
53            type            empty;
54        }
55        front
56        {
57            type            empty;
58        }
59    }
```

- We are using uniform initial conditions (line 19).
- For the **in** patch we are using a **fixedValue** boundary condition.
- For the **out** patch we are using an **inletOutlet** boundary condition (this boundary condition avoids backflow).
- For the **cylinder** patch (which is **base type wall**), we are using the **omegaWallFunction** boundary condition. This is a wall function, we are going to talk about this when we deal with turbulence modeling. Remember, we can use wall functions only if the patch is of **base type wall**.
- The rest of the patches are constrained.
- FYI, the inlet velocity is 1 and the eddy viscosity ratio is equal to 10.

Flow past a cylinder – From laminar to turbulent flow

The file *0/nut*

```
19    internalField   uniform 0;
20
21    boundaryField
22    {
23        out
24        {
25            type            calculated;
26            value           uniform 0;
27        }
28        sym1
29        {
30            type            symmetryPlane;
31        }
32        sym2
33        {
34            type            symmetryPlane;
35        }
36        in
37        {
38            type            calculated;
39            value           uniform 0;
40        }
41        cylinder
42        {
43            type            nutkWallFunction;
44            Cmu             0.09;
45            kappa           0.41;
46            E               9.8;
47            value           uniform 0;
48        }
49        back
50        {
51            type            empty;
52        }
53        front
54        {
55            type            empty;
56        }
57    }
```

- We are using uniform initial conditions (line 19).
- For the **in** patch we are using the **calculated** boundary condition (nut is computed from kappa and omega)
- For the **out** patch we are using the **calculated** boundary condition (nut is computed from kappa and omega)
- For the **cylinder** patch (which is **base type wall**), we are using the **nutkWallFunction** boundary condition. This is a wall function, we are going to talk about this when we deal with turbulence modeling. Remember, we can use wall functions only if the patch is of **base type wall**.
- The rest of the patches are constrained.
- Remember, the turbulent viscosity ν_t (nut) is equal to

$$\frac{\kappa}{\omega}$$

Flow past a cylinder – From laminar to turbulent flow

Running the case – Setting a turbulent case

- You will find this tutorial in the directory **`$PTOFC/101OF/vortex_shedding/c14`**
- Feel free to use the Fluent mesh or the mesh generated with `blockMesh`. In this case we will use `blockMesh`.
- To run this case, in the terminal window type:

1. `$> foamCleanTutorials`
2. `$> blockMesh`
3. `$> renumberMesh -overwrite`
4. `$> pimpleFoam | log`

   You will need to launch this script in a different terminal
5. `$> pyFoamPlotWatcher.py log`

   You will need to launch this script in a different terminal
6. `$> gnuplot scripts0/plot_coeffs`

   You will need to launch this script in a different terminal
7. `$> pimpleFoam -postprocess -func yPlus -latestTime -noFunctionObjects`
8. `$> paraFoam`

Flow past a cylinder – From laminar to turbulent flow

Running the case – Setting a turbulent case

- In step 3 we use the utility `renumberMesh` to make the linear system more diagonal dominant, this will speed-up the linear solvers.
- In step 4 we run the simulation and save the log file. Notice that we are sending the job to background.
- In step 5 we use `pyFoamPlotWatcher.py` to plot the residuals on-the-fly. As the job is running in background, we can launch this utility in the same terminal tab.
- In step 6 we use the gnuplot script `scripts0/plot_coeffs` to plot the force coefficients on-the-fly. Besides monitoring the residuals, is always a good idea to monitor a quantity of interest. Feel free to take a look at the script and to reuse it.
- In step 7 we use the utility `postProcess` to compute the y^+ value of each saved solution (we are going to talk about y^+ when we deal with turbulence modeling).

Flow past a cylinder – From laminar to turbulent flow

`pimpleFoam` **output screen**

```
Courant Number mean: 0.088931706 max: 0.90251464
deltaT = 0.040145538
Time = 499.97

PIMPLE: iteration 1
DILUPBiCG:  Solving for Ux, Initial residual = 0.0028528538, Final residual = 9.5497298e-11, No Iterations 3
DILUPBiCG:  Solving for Uy, Initial residual = 0.0068876991, Final residual = 7.000938e-10, No Iterations 3
GAMG:  Solving for p, Initial residual = 0.25644342, Final residual = 0.00022585963, No Iterations 7
GAMG:  Solving for p, Initial residual = 0.0073871161, Final residual = 5.2798526e-06, No Iterations 8
time step continuity errors : sum local = 3.2664019e-10, global = -1.3568363e-12, cumulative = -9.8446438e-08
GAMG:  Solving for p, Initial residual = 0.16889316, Final residual = 0.00014947209, No Iterations 7
GAMG:  Solving for p, Initial residual = 0.0051876466, Final residual = 3.7123156e-06, No Iterations 8
time step continuity errors : sum local = 2.2950163e-10, global = -8.0710768e-13, cumulative = -9.8447245e-08
PIMPLE: iteration 2
DILUPBiCG:  Solving for Ux, Initial residual = 0.0013482181, Final residual = 4.1395468e-10, No Iterations 3
DILUPBiCG:  Solving for Uy, Initial residual = 0.0032433196, Final residual = 3.3969121e-09, No Iterations 3
GAMG:  Solving for p, Initial residual = 0.10067317, Final residual = 8.9325549e-05, No Iterations 7
GAMG:  Solving for p, Initial residual = 0.0042844521, Final residual = 3.0190597e-06, No Iterations 8
time step continuity errors : sum local = 1.735023e-10, global = -2.0653335e-13, cumulative = -9.8447452e-08
GAMG:  Solving for p, Initial residual = 0.0050231165, Final residual = 3.2656397e-06, No Iterations 8
DICPCG:  Solving for p, Initial residual = 0.00031459519, Final residual = 9.4260163e-07, No Iterations 36
time step continuity errors : sum local = 5.4344408e-11, global = 4.0060595e-12, cumulative = -9.8443445e-08
DILUPBiCG:  Solving for omega, Initial residual = 0.00060510266, Final residual = 1.5946601e-10, No Iterations 3
DILUPBiCG:  Solving for k, Initial residual = 0.0032163247, Final residual = 6.9350899e-10, No Iterations 3
bounding k, min: -3.6865398e-05 max: 0.055400108 average: 0.0015914926
ExecutionTime = 1689.51 s  ClockTime = 1704 s

fieldAverage fieldAverage output:
    Calculating averages

forceCoeffs forceCoeffs_object output:
    Cm    = 0.0023218797
    Cd    = 1.1832452
    Cl    = -1.3927646
    Cl(f) = -0.69406044
    Cl(r) = -0.6987042

fieldMinMax minmaxdomain output:
    min(p) = -1.5466372 at location (-0.040619337 -1.033408 0)
    max(p) = 0.54524589 at location (-1.033408 0.040619337 1.4015759e-17)
    min(U) = (0.94205232 -1.0407426 -5.0319219e-19) at location (-0.70200781 -0.75945224 -1.3630525e-17)
    max(U) = (1.8458167 0.0047368607 4.473279e-19) at location (-0.12989625 -1.0971865 2.4694467e-17)
    min(k) = 1e-15 at location (1.0972618 1.3921931 -2.2329889e-17)
    max(k) = 0.055400108 at location (2.1464795 0.42727634 0)
    min(omega) = 0.2355751 at location (29.403674 19.3304 0)
    max(omega) = 21.477072 at location (1.033408 0.040619337 1.3245285e-17)
```

Courant number

Time step

Simulation time

Outer iteration 1 (nOuterCorrectors)

Outer iteration 2 (nOuterCorrectors)

pFinal

kappa and omega residuals

Message letting you know that the variable is becoming unbounded

Force coefficients

Minimum and maximum values

Flow past a cylinder – From laminar to turbulent flow

The output screen

- This is the output screen of the `yPlus` utility.

```
Time = 500.01
Reading field U

Reading/calculating face flux field phi

Selecting incompressible transport model Newtonian
Selecting RAS turbulence model kOmegaSST
kOmegaSSTCoeffs
{
    alphaK1         0.85;
    alphaK2         1;
    alphaOmega1     0.5;
    alphaOmega2     0.856;
    gamma1          0.55555556;
    gamma2          0.44;
    beta1           0.075;
    beta2           0.0828;
    betaStar        0.09;
    a1              0.31;
    b1              1;
    c1              10;
    F3              false;
}

Patch 4 named cylinder y+ : min: 0.94230389 max: 12.696632 average: 7.3497345

Writing yPlus to field yPlus
```

Transport model

Turbulence model

Model coefficients

Patch where we are computing y+

Minimum, maximum and average values

Writing the field to the solution directory

Flow past a cylinder – From laminar to turbulent flow

Using a compressible solver

- So far we have only used incompressible solvers.
- Let us use the compressible solver `rhoPimpleFoam`, which is a

  Transient solver for laminar or turbulent flow of compressible fluids for HVAC and similar applications. Uses the flexible PIMPLE (PISO-SIMPLE) solution for time-resolved and pseudo-transient simulations.

- When working with compressible solver we need to define the thermodynamical properties of the working fluid and the temperature field (we are also solving the energy equation)
- This case is already setup in the directory

```
$PTOFC/101OF/vortex_shedding/c24
```

Flow past a cylinder – From laminar to turbulent flow

- The following dictionaries remain unchanged
    - `system/blockMeshDict`
    - `constant/polyMesh/boundary`

- Reminder:
    - The diameter of the cylinder is 0.002 m.
    - The working fluid is air at 20° Celsius and at a sea level.
    - Isothermal flow.
    - And we are targeting for a Re = 200.

$$\nu = \frac{\mu}{\rho} \qquad Re = \frac{\rho \times U \times D}{\mu} = \frac{U \times D}{\nu}$$

Flow past a cylinder – From laminar to turbulent flow

The **`constant`** directory

- In this directory, we will find the following compulsory dictionary files:

  - *`thermophysicalProperties`*
  - *`turbulenceProperties`*

- *`thermophysicalProperties`* contains the definition of the physical properties of the working fluid.
- *`turbulenceProperties`* contains the definition of the turbulence model to use.

Flow past a cylinder – From laminar to turbulent flow

The *thermophysicalProperties* dictionary file

```
18  thermoType
19  {
20      type            hePsiThermo;
21      mixture         pureMixture;
22      transport       const;
23      thermo          hConst;
24      equationOfState perfectGas;
25      specie          specie;
26      energy          sensibleEnthalpy;
27  }
28
29  mixture
30  {
31      specie
32      {
33          nMoles      1;
34          molWeight   28.9;
35      }
36      thermodynamics
37      {
38          Cp          1005;
39          Hf          0;
40      }
41      transport
42      {
43          mu          1.84e-05;
44          Pr          0.713;
45      }
46  }
```

- This dictionary file is located in the directory **constant**. Thermophysical models are concerned with energy, heat and physical properties.
- In the sub-dictionary **thermoType** (lines 18-27), we define the thermophysical models.
- The **transport** modeling concerns evaluating dynamic viscosity (line 22). In this case the viscosity is constant.
- The thermodynamic models (**thermo**) are concerned with evaluating the specific heat Cp (line 23). In this case Cp is constant
- The **equationOfState** keyword (line 24) concerns to the equation of state of the working fluid. In this case

$$\rho = \frac{p}{RT}$$

- The form of the energy equation to be used in the solution is specified in line 26 (**energy**). In this case we are using enthalpy (**sensibleEnthalpy**).

Flow past a cylinder – From laminar to turbulent flow

The *thermophysicalProperties* dictionary file

```
18    thermoType
19    {
20        type            hePsiThermo;
21        mixture         pureMixture;
22        transport       const;
23        thermo          hConst;
24        equationOfState perfectGas;
25        specie          specie;
26        energy          sensibleEnthalpy;
27    }
28
29    mixture
30    {
31        specie
32        {
33            nMoles      1;
34            molWeight   28.9;
35        }
36        thermodynamics
37        {
38            Cp          1005;
39            Hf          0;
40        }
41        transport
42        {
43            mu          1.84e-05;
44            Pr          0.713;
45        }
46    }
```

- In the sub-dictionary **mixture** (lines 29-46), we define the thermophysical properties of the working fluid.
- In this case, we are defining the properties for air at 20° Celsius and at a sea level.

Flow past a cylinder – From laminar to turbulent flow

The *turbulenceProperties* dictionary file

- In this dictionary file we select what model we would like to use (laminar or turbulent).
- This dictionary is compulsory.
- As we do not want to model turbulence, the dictionary is defined as follows,

```
17    simulationType    laminar;
```

Flow past a cylinder – From laminar to turbulent flow

The **0** directory

- In this directory, we will find the dictionary files that contain the boundary and initial conditions for all the primitive variables.
- As we are solving the compressible laminar Navier-Stokes equations, we will find the following field files:

  - `p` (pressure)
  - `T` (temperature)
  - `U` (velocity field)

Flow past a cylinder – From laminar to turbulent flow

The file *0/p*

```
17    dimensions      [1 -1 -2 0 0 0 0];
18
19    internalField   uniform 101325;
20
21    boundaryField
22    {
23        in
24        {
25            type            zeroGradient;
26        }
28        out
29        {
30            type            fixedValue;
31            value           uniform 101325;
32        }
34        cylinder
35        {
36            type            zeroGradient;
37        }
39        sym1
40        {
41            type            symmetryPlane;
42        }
44        sym2
45        {
46            type            symmetryPlane;
47        }
49        back
50        {
51            type            empty;
52        }
54        front
55        {
56            type            empty;
57        }
58    }
```

- This file contains the boundary and initial conditions for the scalar field pressure (**p**). **We are working with absolute pressure.**
- Contrary to incompressible flows where we defined relative pressure, this is the absolute pressure.
- Also, pay attention to the units (line 17). The pressure is defined in Pascal.
- We are using uniform initial conditions (line 19).
- For the **in** patch we are using a **zeroGradient** boundary condition.
- For the **outlet** patch we are using a **fixedValue** boundary condition.
- For the **cylinder** patch we are using a **zeroGradient** boundary condition.
- The rest of the patches are constrained.

Flow past a cylinder – From laminar to turbulent flow

The file *0/T*

```
17    dimensions      [0 0 0 -1 0 0 0];
18
19    internalField   uniform 293.15;
20
21    boundaryField
22    {
23        in
24        {
25            type            fixedValue;
26            value           $internalField;
27        }
29        out
30        {
31            type            inletOutlet;
32            value           $internalField;
33            inletValue      $internalField;
34        }
36        cylinder
37        {
38            type            zeroGradient;
39        }
41        sym1
42        {
43            type            symmetryPlane;
44        }
46        sym2
47        {
48            type            symmetryPlane;
49        }
51        back
52        {
53            type            empty;
54        }
56        front
57        {
58            type            empty;
59        }
60    }
```

- This file contains the boundary and initial conditions for the scalar field temperature (**T**).
- Also, pay attention to the units (line 17). The temperature is defined in Kelvin.
- We are using uniform initial conditions (line 19).
- For the **in** patch we are using a **fixedValue** boundary condition.
- For the **out** patch we are using a **inletOutlet** boundary condition (in case of backflow).
- For the **cylinder** patch we are using a **zeroGradient** boundary condition.
- The rest of the patches are constrained.

Flow past a cylinder – From laminar to turbulent flow

The file *0/U*

```
17    dimensions      [0 1 -1 0 0 0 0];
18
19    internalField   uniform (1.5 0 0);
20
21    boundaryField
22    {
23        in
24        {
25            type            fixedValue;
26            value           uniform (1.5 0 0);
27        }
29        out
30        {
31             type            inletOutlet;
32             phi             phi;
33             inletValue      uniform (0 0 0);
34             value           uniform (0 0 0);
35        }
37        cylinder
38        {
39            type            fixedValue;
40            value           uniform (0 0 0);
41        }
43        sym1
44        {
45            type            symmetryPlane;
46        }
48        sym2
49        {
50            type            symmetryPlane;
51        }
53        back
54        {
55            type            empty;
56        }
58        front
59        {
60            type            empty;
61        }
62    }
```

- This file contains the boundary and initial conditions for the dimensional vector field **U**.
- We are using uniform initial conditions and the numerical value is **(1.5 0 0)** (keyword **internalField** in line 19).
- For the **in** patch we are using a **fixedValue** boundary condition.
- For the **out** patch we are using a **inletOutlet** boundary condition (in case of backflow).
- For the **cylinder** patch we are using a **zeroGradient** boundary condition.
- The rest of the patches are constrained.

Flow past a cylinder – From laminar to turbulent flow

The **`system`** directory

- The **`system`** directory consists of the following compulsory dictionary files:
    - *`controlDict`*
    - *`fvSchemes`*
    - *`fvSolution`*

- *`controlDict`* contains general instructions on how to run the case.
- *`fvSchemes`* contains instructions for the discretization schemes that will be used for the different terms in the equations.
- *`fvSolution`* contains instructions on how to solve each discretized linear equation system.

Flow past a cylinder – From laminar to turbulent flow

The `controlDict` dictionary

```
17      application     icoFoam;
18
19      startFrom       startTime;
20      //startFrom       latestTime;
21
22      startTime       0;
23
24      stopAt          endTime;
25      //stopAt  writeNow;
26
27      endTime         0.3;
28
29      deltaT          0.00001;
30
31      writeControl    adjustableRunTime;
32
33      writeInterval   0.0025;
34
35      purgeWrite      0;
36
37      writeFormat     ascii;
38
39      writePrecision  10;
40
41      writeCompression off;
42
43      timeFormat      general;
44
45      timePrecision   6;
46
47      runTimeModifiable true;
48
49      adjustTimeStep  yes;
50      maxCo           1;
51      maxDeltaT       1;
```

- This case will start from the last saved solution (**startFrom**). If there is no solution, the case will start from time 0 (**startTime**).
- It will run up to 0.3 seconds (**endTime**).
- The initial time step of the simulation is 0.00001 seconds (**deltaT**).
- It will write the solution every 0.0025 seconds (**writeInterval**) of simulation time (**adjustableRunTime**). The option **adjustableRunTime** will adjust the time-step to save the solution at the precise intervals. This may add some oscillations in the solution as the CFL is changing.
- It will keep all the solution directories (**purgeWrite**).
- It will save the solution in ascii format (**writeFormat**).
- And as the option **runTimeModifiable** is on, we can modify all these entries while we are running the simulation.
- In line 49 we turn on the option **adjustTimeStep**. This option will automatically adjust the time step to achieve the maximum desired courant number (line 50).
- We also set a maximum time step in line 51.
- Remember, the first time step of the simulation is done using the value set in line 28 and then it is automatically scaled to achieve the desired maximum values (lines 66-67).
- The feature **adjustTimeStep** is only present in the **PIMPLE** family solvers, but it can be added to any solver by modifying the source code.

Flow past a cylinder – From laminar to turbulent flow

The `controlDict` dictionary

```
55      functions
56      {

178     forceCoeffs_object
179     {
188      type forceCoeffs;
189      functionObjectLibs ("libforces.so");
190      patches (cylinder);
191
192      pName p;
193      Uname U;
194      //rhoName rhoInf;
195      rhoInf 1.205;
196
197      //// Dump to file
198      log true;
199
200      CofR (0.0 0 0);
201      liftDir (0 1 0);
202      dragDir (1 0 0);
203      pitchAxis (0 0 1);
204      magUInf 1.5;
205      lRef 0.001;
206      Aref 0.000002;
207
208       outputControl   timeStep;
209       outputInterval  1;
210       }

235
236     };
```

- As usual, at the bottom of the `controlDict` dictionary file we define the **functionObjects** (lines 55-236).
- Of special interest is the **functionObject forceCoeffs_object**.
- As we changed the domain dimensions and the inlet velocity we need to update the reference values (lines 204-206).
- It is also important to update the reference density (line 195).

Flow past a cylinder – From laminar to turbulent flow

The *fvSchemes* dictionary

```
ddtSchemes
{
    default         Euler;
}

gradSchemes
{
    default           cellLimited leastSquares 1;
}

divSchemes
{
    default         none;
    div(phi,U)      Gauss linearUpwindV default;

    div(phi,K)      Gauss linear;
    div(phi,h)      Gauss linear;

    div(((rho*nuEff)*dev2(T(grad(U))))) Gauss linear;
}

laplacianSchemes
{
    default         Gauss linear limited 1;
}

interpolationSchemes
{
    default         linear;
}

snGradSchemes
{
    default         limited 1;
}
```

- In this case, for time discretization (**ddtSchemes**) we are using the **Euler** method.
- For gradient discretization (**gradSchemes**) we are using the **leastSquares** method.
- For the discretization of the convective terms (**divSchemes**) we are using **linearUpwind** interpolation with no slope limiters for the term **div(phi,U)**.
- For the terms **div(phi,K)** (kinetic energy) and **div(phi,h)** (enthalpy) we are using **linear** interpolation method with no slope limiters.
- For the term **div(((rho*nuEff)*dev2(T(grad(U)))))** we are using **linear** interpolation (this term is related to the turbulence modeling).
- For the discretization of the Laplacian (**laplacianSchemes** and **snGradSchemes**) we are using the **Gauss linear limited 1** method.
- This method is second order accurate.

Flow past a cylinder – From laminar to turbulent flow

The *fvSolution* dictionary

```
17      solvers
18      {
20          p
21          {
22              solver          PCG;
23              preconditioner  DIC;
24              tolerance       1e-06;
25              relTol          0.01;
26              minIter          2;
27          }
46          pFinal
47          {
48              $p;
49              relTol          0;
50              minIter          2;
51          }
53          "U.*"
54          {
55              solver          PBiCGStab;
56              preconditioner  DILU;
57              tolerance       1e-08;
58              relTol          0;
59              minIter          2;
60          }
74          hFinal
75          {
76              solver          PBiCGStab;
77              preconditioner  DILU;
78              tolerance       1e-08;
79              relTol          0;
80              minIter          2;
81          }
83          "rho.*"
84          {
85              solver         diagonal;
86          }
87      }
```

- To solve the pressure (**p**) we are using the **PCG** method with an absolute **tolerance** of 1e-6 and a relative tolerance **relTol** of 0.01.
- The entry **pFinal** refers to the final correction of the **PISO** loop. Notice that we are using macro expansion (**$p)** to copy the entries from the sub-dictionary **p**.
- To solve **U** and **UFinal** (**U.***) we are using the solver **PBiCGStab** with an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0.
- To solve **hFinal** (enthalpy) we are using the solver **PBiCGStab** with an absolute **tolerance** of 1e-8 and a relative tolerance **relTol** of 0.
- To solve **rho** and **rhoFinal** (**rho.***) we are using the **diagonal** solver (remember rho is found from the equation of state, so this is a back-substitution).
- FYI, solving for the velocity is relative inexpensive, whereas solving for the pressure is expensive.
- Be careful with the enthalpy, it might cause oscillations.

Flow past a cylinder – From laminar to turbulent flow

The *fvSolution* dictionary

```
88
89      PIMPLE
90      {
91          momentumPredictor yes;
92          nOuterCorrectors 1;
93          nCorrectors      2;
94          nNonOrthogonalCorrectors 1;
95          rhoMin           0.5;
96          rhoMax           2.0;
97      }
```

- The **PIMPLE** sub-dictionary contains entries related to the pressure-velocity coupling (in this case the **PIMPLE** method).
- Setting the keyword **nOuterCorrectors** to 1 is equivalent to running using the **PISO** method.
- Hereafter we are doing 2 **PISO** correctors (**nCorrectors**) and 1 non-orthogonal corrections (**nNonOrthogonalCorrectors**).
- In lines 95-96 we set the minimum and maximum physical values of rho (density).
- If we increase the number of **nCorrectors** and **nNonOrthogonalCorrectors** we gain more stability but at a higher computational cost.
- The choice of the number of corrections is driven by the quality of the mesh and the physics involve.
- You need to do at least one **PISO** loop (**nCorrectors**).

Flow past a cylinder – From laminar to turbulent flow

Running the case – Using a compressible solver

- You will find this tutorial in the directory **`$PTOFC/101OF/vortex_shedding/c24`**
- Feel free to use the Fluent mesh or the mesh generated with `blockMesh`. In this case we will use `blockMesh`.
- To run this case, in the terminal window type:

1. `$> foamCleanTutorials`
2. `$> blockMesh`
3. `$> transformPoints -scale '(0.001 0.001 0.001)'`
4. `$> renumberMesh -overwrite`
5. `$> rhoPimpleFoam | tee log`
6. `$> pyFoamPlotWatcher.py log`

   You will need to launch this script in a different terminal
7. `$> gnuplot scripts0/plot_coeffs`

   You will need to launch this script in a different terminal
8. `$> rhoPimpleFoam -postProcess -func MachNo`
9. `$> paraFoam`

Flow past a cylinder – From laminar to turbulent flow

Running the case – Using a compressible solver

- In step 3 we scale the mesh.
- In step 4 we use the utility `renumberMesh` to make the linear system more diagonal dominant, this will speed-up the linear solvers.
- In step 5 we run the simulation and save the log file. Notice that we are sending the job to background.
- In step 6 we use `pyFoamPlotWatcher.py` to plot the residuals on-the-fly. As the job is running in background, we can launch this utility in the same terminal tab.
- In step 7 we use the gnuplot script `scripts0/plot_coeffs` to plot the force coefficients on-the-fly. Besides monitoring the residuals, is always a good idea to monitor a quantity of interest. Feel free to take a look at the script and to reuse it.
- In step 8 we use the utility `MachNo` to compute the Mach number.

Flow past a cylinder – From laminar to turbulent flow

`rhoPimpleFoam` **output screen**

```
Courant Number mean: 0.1280224248 max: 0.9885863338
deltaT = 3.816512052e-05
Time = 0.3

diagonal:  Solving for rho, Initial residual = 0, Final residual = 0, No Iterations 0
PIMPLE: iteration 1
DILUPBiCG:  Solving for Ux, Initial residual = 0.003594731129, Final residual = 3.026673755e-11, No Iterations 5
DILUPBiCG:  Solving for Uy, Initial residual = 0.01296036298, Final residual = 1.223236662e-10, No Iterations 5
DILUPBiCG:  Solving for h, Initial residual = 0.01228951539, Final residual = 2.583236461e-09, No Iterations 4
DICPCG:  Solving for p, Initial residual = 0.01967621449, Final residual = 8.797612158e-07, No Iterations 77
DICPCG:  Solving for p, Initial residual = 0.003109422612, Final residual = 9.943030465e-07, No Iterations 69
diagonal:  Solving for rho, Initial residual = 0, Final residual = 0, No Iterations 0
time step continuity errors : sum local = 6.835363016e-11, global = 4.328592697e-12, cumulative = 2.366774797e-09
rho max/min : 1.201420286 1.201382023
DICPCG:  Solving for p, Initial residual = 0.003160602108, Final residual = 9.794177338e-07, No Iterations 69
DICPCG:  Solving for p, Initial residual = 0.0004558492254, Final residual = 9.278622052e-07, No Iterations 58
diagonal:  Solving for rho, Initial residual = 0, Final residual = 0, No Iterations 0
time step continuity errors : sum local = 6.38639685e-11, global = 1.446434866e-12, cumulative = 2.368221232e-09
rho max/min : 1.201420288 1.201381976
ExecutionTime = 480.88 s  ClockTime = 490 s

faceSource inMassFlow output:
    sum(in) of phi = -7.208447027e-05

faceSource outMassFlow output:
    sum(out) of phi = 7.208444452e-05

fieldAverage fieldAverage output:
    Calculating averages

    Writing average fields

forceCoeffs forceCoeffs_object output:
    Cm    = -0.001269886395
    Cd    = 1.419350733
    Cl    = 0.6247248606
    Cl(f) = 0.3110925439
    Cl(r) = 0.3136323167

fieldMinMax minmaxdomain output:
    min(p) = 101322.7878 at location (-0.0001215826043 0.001027092827 0)
    max(p) = 101326.4972 at location (-0.001033408037 -4.061934599e-05 0)
    min(U) = (-0.526856427 -0.09305459972 -8.110485132e-25) at location (0.002039092041 -0.0004058872656 -3.893823418e-20)
    max(U) = (2.184751599 0.2867627526 4.83091257e-25) at location (0.0001663574444 0.001404596295 0)
    min(T) = 293.1487423 at location (-5.556854517e-05 0.001412635233 0)
    max(T) = 293.1509903 at location (-0.00117685237 -4.627394552e-05 3.016083257e-20)
```

Courant number

Time step

Solving for density (rho)

h residuals

pFinal

Solving for density (rhoFinal)

Max/min density values

Force coefficients

Minimum and maximum values

Flow past a cylinder – From laminar to turbulent flow

- In the directory **`$PTOFC/101OF/vortex_shedding`**, you will find 28 variations of the cylinder case involving different solvers and models. Feel free to explore all them.
- This is what you will find in each directory,
  - c1 = blockMesh – icoFoam – Re = 200.
  - c2 = fluentMeshToFoam – icoFoam – Re = 200.
  - c3 = blockMesh – icoFoam – Field initialization – Re = 200.
  - c4 = blockMesh – potentialFoam – Re = 200.
  - c5 = blockMesh – mapFields – icoFoam – original mesh – Re = 200.
  - c6 = blockMesh – mapFields – icoFoam – Finer mesh – Re = 200.
  - c7 = blockMesh – pimpleFoam – Re = 200 – No turbulent model.
  - c8 = blockMesh – pisoFoam – Re = 200 – No turbulent model.
  - c9 = blockMesh – pisoFoam – Re = 200 – K-Omega SST turbulent model.
  - c10 = blockMesh – simpleFoam – Re = 200 – No turbulent model.
  - c11 = blockMesh – simpleFoam – Re = 40 – No turbulent model.
  - c12 = blockMesh – pisoFoam – Re = 40 – No turbulent model.
  - c14 = blockMesh – pimpleFoam – Re = 10000 – K-Omega SST turbulent model with wall functions.
  - c15 = blockMesh – pimpleFoam – Re = 100000 – K-Omega SST turbulent model with wall functions.

Flow past a cylinder – From laminar to turbulent flow

- This is what you will find in each directory,
  - c16 = blockMesh – simpleFoam – Re = 100000 – K-Omega SST turbulent model with no wall functions.
  - c17 = blockMesh – simpleFoam – Re = 100000 – K-Omega SST turbulent model with wall functions.
  - c18 = blockMesh – pisoFoam – Re = 100000, LES Smagorinsky turbulent model.
  - c19 = blockMesh – pimpleFoam – Re = 1000000 – Spalart Allmaras turbulent model with no wall functions.
  - c20 = blockMesh – sonicFoam – Mach = 2.0 – Compressible – Laminar.
  - c21 = blockMesh – sonicFoam – Mach = 2.0 – Compressible – K-Omega SST turbulent model with wall functions.
  - c22 = blockMesh – pimpleFoam – Re = 200 – No turbulent model – Source terms (momentum)
  - c23 = blockMesh – pimpleFoam – Re = 200 – No turbulent model – Source terms (scalar transport)
  - c24 = blockMesh – rhoPimpleFoam – Re = 200 – Laminar, isothermal
  - c25 = blockMesh – rhoPimpleFoam – Re = 20000 – Turbulent, compressible
  - c26 = blockMesh – pimpleDyMFoam – Re = 200 – Laminar, moving cylinder (oscillating).
  - c27 = blockMesh – pimpleDyMFoam/pimpleFoam – Re = 200 – Laminar, rotating cylinder using AMI patches.
  - c28 = blockMesh – interFoam – Laminar, multiphase, free surface.
  - c29 = blockMesh – pimpleFoam laminar with source terms and AMR.