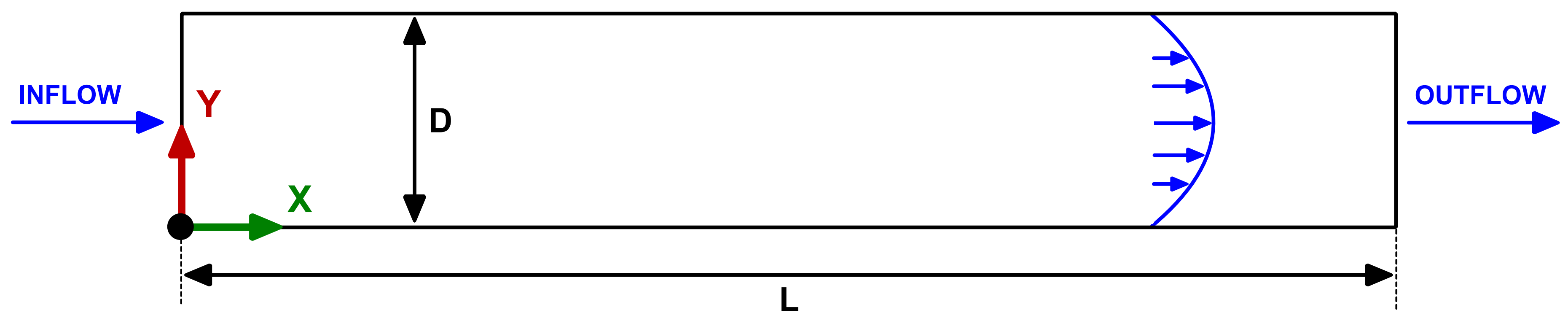
A simple validation case – Hagen-Poiseuille solution



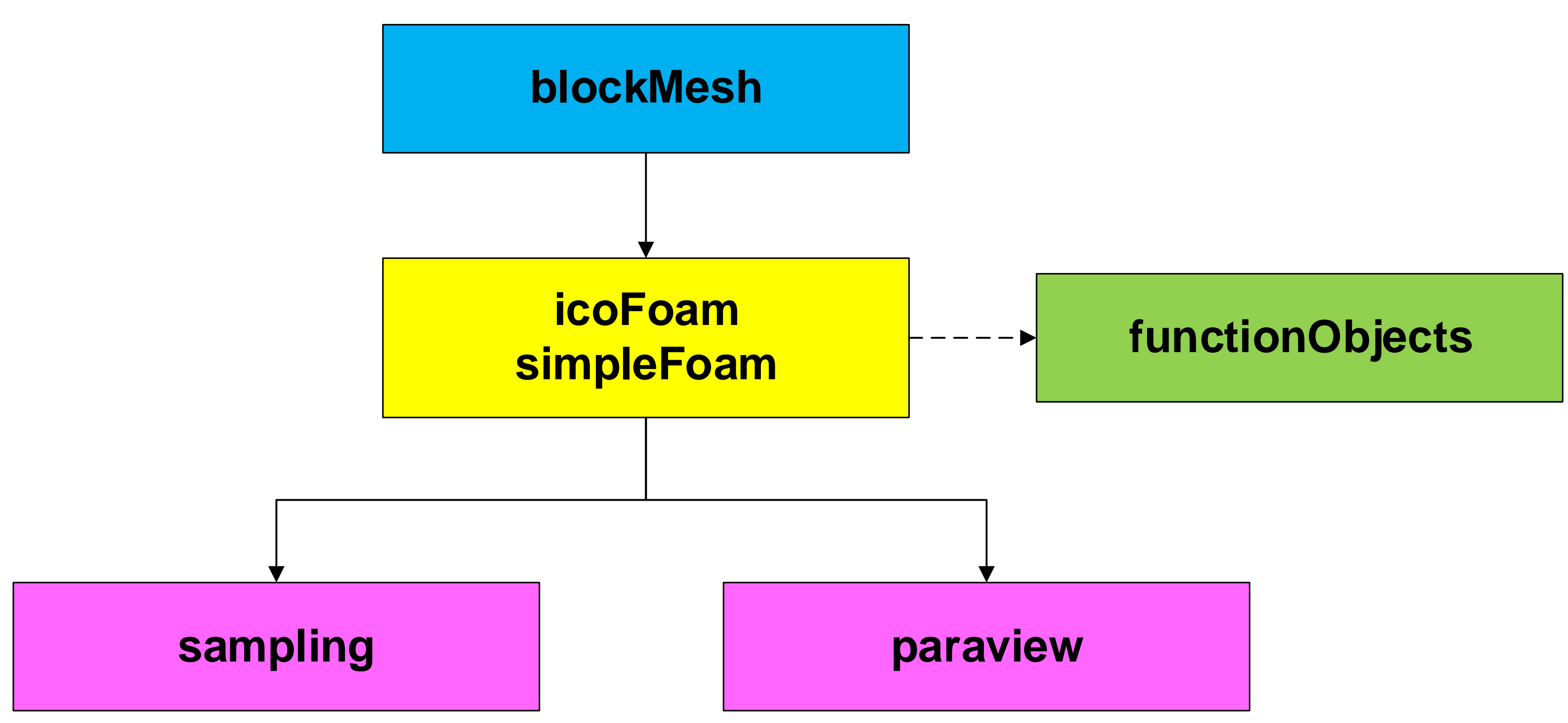
Physical and numerical side of the problem:

- The governing equations of the problem are the incompressible laminar Navier-Stokes equations.
- We are going to work in a 2D domain but the problem can be extended to 3D or axisymmetric problems easily.
- This problem has an analytical solution for the parabolic velocity profile

$$u = u_{max}\left[1 - \left(\frac{r}{r_{pipe}}\right)^2\right]$$

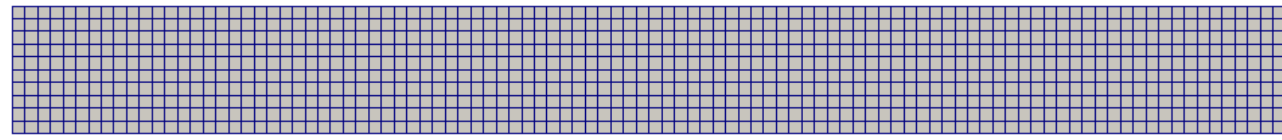
A simple validation case – Hagen-Poiseuille solution

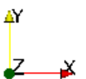
Workflow of the case



A simple validation case – Hagen-Poiseuille solution

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





Mesh (coarse add 2D)

- This mesh is very coarse but for the physics involved it works fine.
- You can try to do successive refinements of this mesh in order to do a mesh independency study.
- If you deal with turbulence, you will need to refine the mesh close to the walls in order to resolve the oudnayr layers.

A simple validation case – Hagen-Poiseuille solution

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

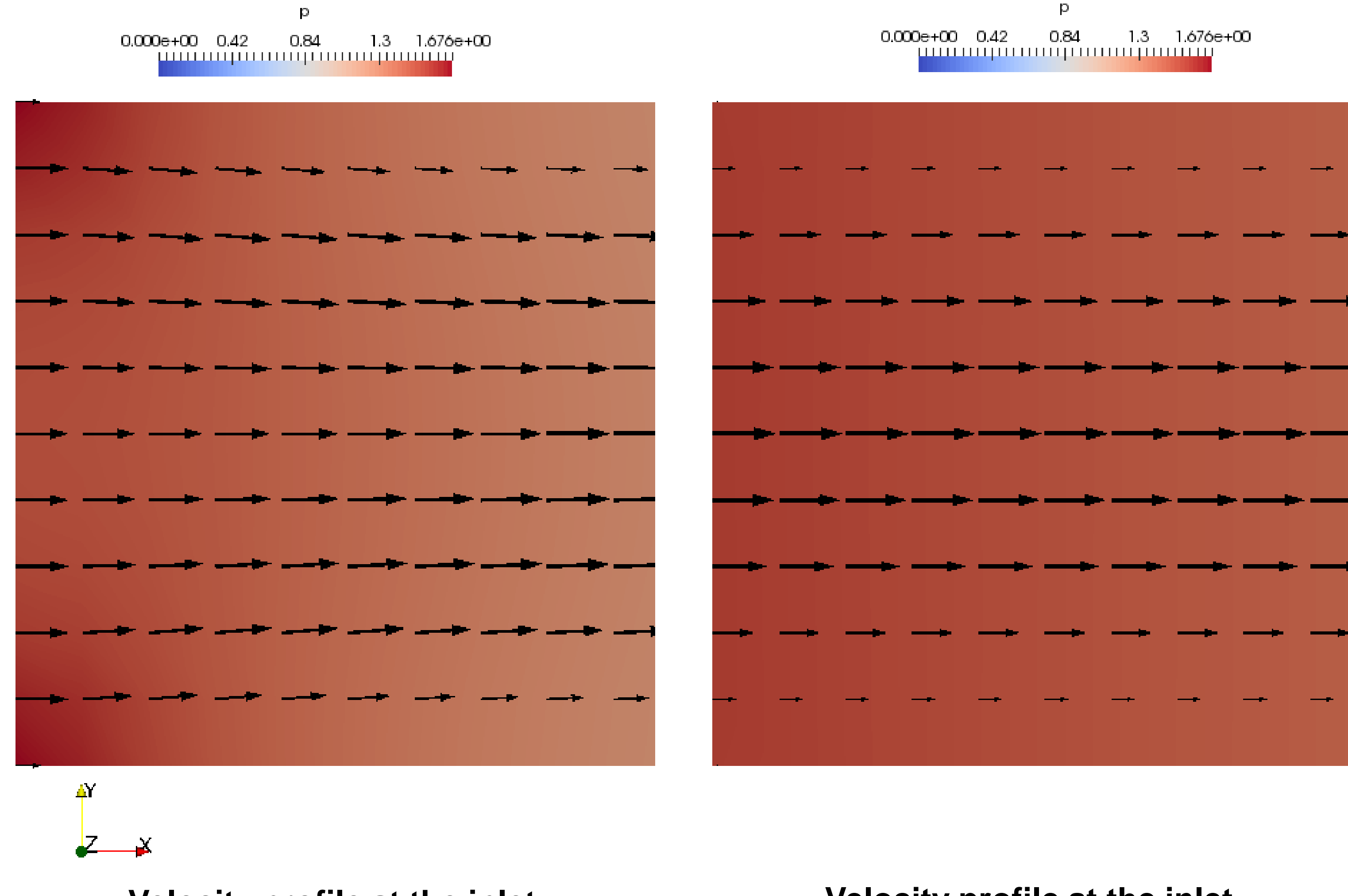
Inlet boundary condition: fix uniform velocity. Left figure: velocity magnitude. Right figure: relative pressure

---

Inlet boundary condition: fix pressure. Left figure: velocity magnitude. Right figure: relative pressure

A simple validation case – Hagen-Poiseuille solution

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

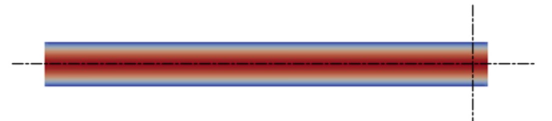


Velocity profile at the inlet
BC: fix uniform velocity

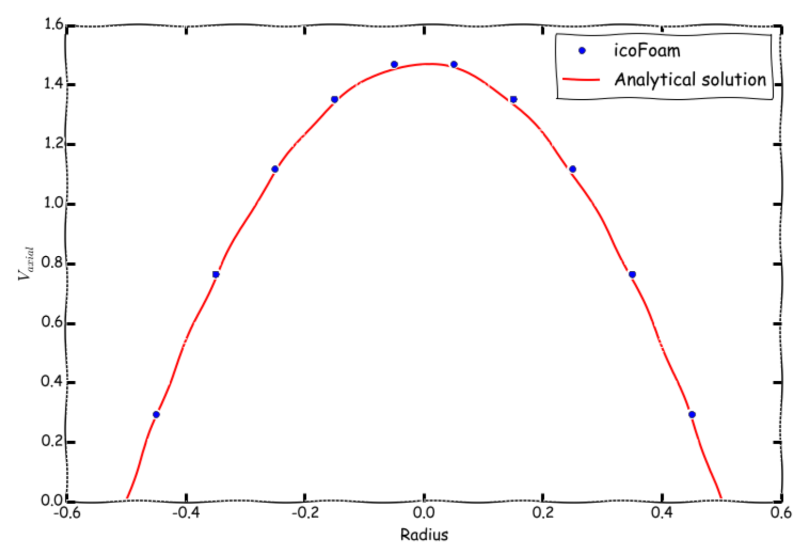
Velocity profile at the inlet
BC: fix pressure

A simple validation case – Hagen-Poiseuille solution

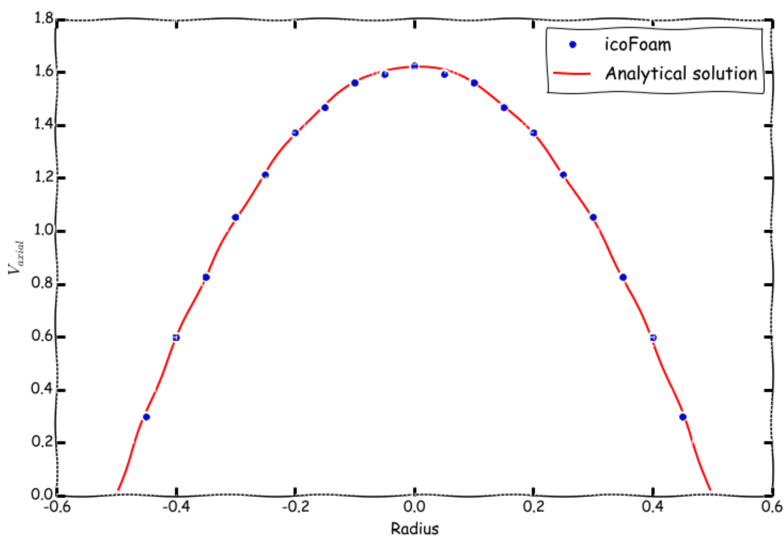
At the end of the day you should get something like this



And as CFD is not only about pretty colors, we should also validate the results



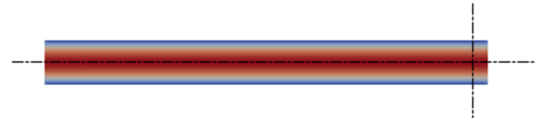
Velocity profile at the outlet
BC: fix uniform velocity



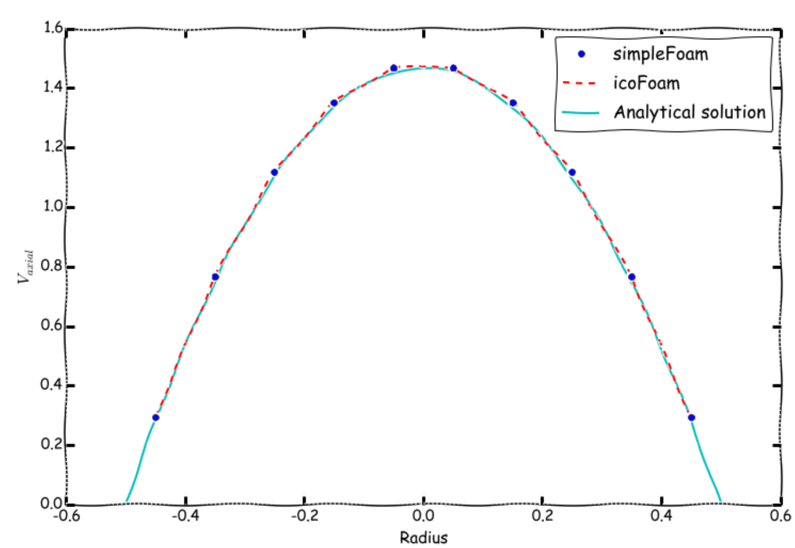
Velocity profile at the outlet
BC: fix pressure

A simple validation case – Hagen-Poiseuille solution

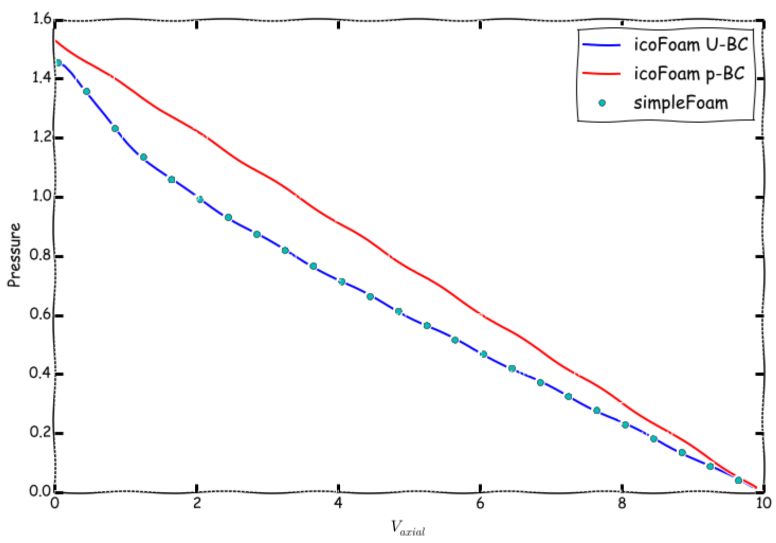
At the end of the day you should get something like this



And as CFD is not only about pretty colors, we should also validate the results



Velocity profile at the outlet
simpleFoam vs. icoFoam vs. analytical solution



Pressure along the axis of the pipe
Comparison of the three cases
(icoFoam BC1, icoFoam BC2, simpleFoam)

A simple validation case – Hagen-Poiseuille solution

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

```
$PTOFC/laminar_pipe
```

- $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.

A simple validation case – Hagen-Poiseuille solution

Loading OpenFOAM® environment

- If you are using our virtual machine or using the lab workstations, you will need to source OpenFOAM® (load OpenFOAM® environment).

- To source OpenFOAM®, type in the terminal:

  - `$> of6x`

- To use PyFoam you will need to source it. Type in the terminal:

  - `$> anaconda2` or `anaconda3`

- Remember, every time you open a new terminal window you need to source OpenFOAM® and PyFoam.

- By default, when installing OpenFOAM® and PyFoam you do not need to do this. This is our choice as we have many things installed and we want to avoid conflicts between applications.

A simple validation case – Hagen-Poiseuille solution

What are we going to do?

- We will use this case to compare the numerical solution with the analytical solution.
- We will compare the solutions obtained when using different inlet boundary conditions.
- To find the numerical solution we will use two different solvers, namely, `icoFoam` and `simpleFoam`.
- `icoFoam` is a transient solver for incompressible, laminar flow of Newtonian fluids.
- `simpleFoam` is a steady-state solver for incompressible, laminar/turbulent flows.
- After finding the numerical solution we will do some sampling.
- Then we will do some plotting (using gnuplot or Python) and scientific visualization.

A simple validation case – Hagen-Poiseuille solution

Let us explore the case directory

A simple validation case – Hagen-Poiseuille solution

The *blockMeshDict* dictionary file

```
17      convertToMeters 1;
18
19      xmin 0;
20      xmax 10;
21      ymin -0.5;
22      ymax 0.5;
23      zmin 0;
24      zmax 0.1;
25
26      vertices
27      (
28          ($xmin  $ymin  $zmin)       //vertex 0
29          ($xmax  $ymin  $zmin)       //vertex 1
30          ($xmax  $ymax  $zmin)       //vertex 2
31          ($xmin  $ymax  $zmin)       //vertex 3
32          ($xmin  $ymin  $zmax)       //vertex 4
33          ($xmax  $ymin  $zmax)       //vertex 5
34          ($xmax  $ymax  $zmax)       //vertex 6
35          ($xmin  $ymax  $zmax)       //vertex 7
36      );
37
38      blocks
39      (
40          hex (0 1 2 3 4 5 6 7) (100 10 1)
            simpleGrading (1 1 1)
41      );
42
43     edges
44     (
45     );
```

- This dictionary is located in the **`system`** directory.
- We are not using scaling.
- **X**/**Y**/**Z** dimensions: **10.0**/**1.0**/**0.1**
- We are using one single block with uniform grading.
- Cells in the **X**, **Y**, and **Z** directions: **100** x **10** x **1** (there is only one cell in the **Z** direction because the mesh is 2D).
- All edges are straight lines by default.

A simple validation case – Hagen-Poiseuille solution

The *blockMeshDict* dictionary file

```
47    boundary
48    (
49        top
50        {
51            type wall;
52            faces
53            (
54                (3 7 6 2)
55            );
56        }
57        inlet
58        {
59            type patch;
60            faces
61            (
62                (0 4 7 3)
63            );
64        }
65        outlet
66        {
67            type patch;
68            faces
69            (
70                (2 6 5 1)
71            );
72        }
73        bottom
74        {
75            type wall;
76            faces
77            (
78                (1 5 4 0)
79            );
80        }
```

- The boundary patches **top** and **bottom** are of **base type** wall.
- The boundary patches **outlet** and **inlet** are of **base type** patch.
- Later on, we will assign the **primitive type** boundary conditions (numerical values), in the field files found in the directory ***0***

A simple validation case – Hagen-Poiseuille solution

The *blockMeshDict* dictionary file

```
81          back
82          {
83              type empty;
84              faces
85              (
86                  (0 3 2 1)
87              );
88          }
89          front
90          {
91              type empty;
92              faces
93              (
94                  (4 5 6 7)
95              );
96          }
97      );
98
99      mergePatchPairs
100     (
101     );
```

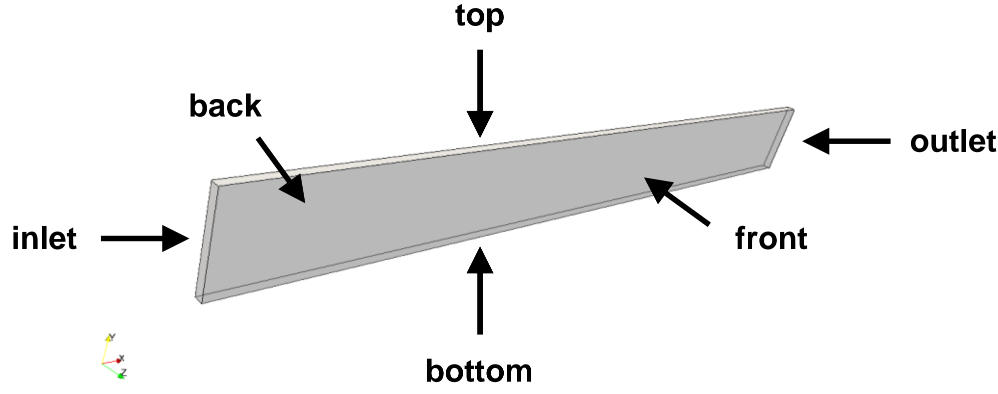
- The boundary patches **back** and **front** are of **base type** empty.
- Later on, we will assign the **primitive type** boundary conditions (numerical values), in the field files found in the directory ***0***
- We do not need to merge faces (we have one single block).

A simple validation case – Hagen-Poiseuille solution

The *boundary* dictionary file

```
18    6
19    (
20        top
21        {
22            type            wall;
24            nFaces          100;
25            startFace       1890;
26        }
27        inlet
28        {
29            type            patch;
30            nFaces          10;
31            startFace       1990;
32        }
33        outlet
34        {
35            type            patch;
36            nFaces          10;
37            startFace       2000;
38        }
39        bottom
40        {
41            type            wall;
43            nFaces          100;
44            startFace       2010;
45        }
46        back
47        {
48            type            empty;
50            nFaces          1000;
51            startFace       2110;
52        }
53        front
54        {
55            type            empty;
57            nFaces          1000;
58            startFace       3110;
59        }
60    )
```

- This dictionary is located in the **`constant/polyMesh`** directory.
- This file was automatically created when generating the mesh.
- In this case, we do not need to modify this file. All the **base type** boundary conditions and **name** of the patches were assigned in the *blockMeshDict* file.
- In you change the **name** or the **base type** of a boundary patch, you will need to modify the field files in the directory `0`.



A simple validation case – Hagen-Poiseuille solution

The *transportProperties* dictionary file

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

```
18    nu                nu [ 0 2 -1 0 0 0 0 ] 0.01;
```

- You can change this value on-the-fly.
- Reminder:
  - The pipe diameter and length are 0.5 m and 10 m, respectively.
  - And we are targeting for a Re = 100.

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

A simple validation case – Hagen-Poiseuille solution

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 incompressible laminar Navier-Stokes equations, we will find the following field variables files:
  - `p` (pressure field)
  - `U` (velocity field)

A simple validation case – Hagen-Poiseuille solution

The file *0/p*

```
19    internalField   uniform 0;
20    //internalField   uniform 101325;
21
22    boundaryField
23    {
24        inlet
25        {
26            type                zeroGradient;
27        }
28
29        outlet
30        {
31            type                fixedValue;
32            value               $internalField;
33
34            //type          zeroGradient;
35        }
36
37        top
38        {
39            type          zeroGradient;
40        }
```

- We are using uniform initial conditions and the numerical value is 0 (keyword **internalField** in line 19). **This is relative pressure.**
- For the **inlet** patch (lines 24-27), we are using a **zeroGradient** boundary condition (we are just extrapolating the internal values to the boundary face).
- For the **outlet** patch (lines 29-35), we are using a **fixedValue** boundary condition with a numerical value equal to 0**.** Notice that we are using macro expansion to assign the numerical value (**$internalField** is equivalent to **uniform 0**).
- For the **top** patch (lines 37-40), we are using a **zeroGradient** boundary condition (we are just extrapolating the internal values to the boundary face).

A simple validation case – Hagen-Poiseuille solution

The file *0/p*

```
42          bottom
43          {
44              type            zeroGradient;
45          }
46
47          front
48          {
49              type                empty;
50          }
51
52          back
53          {
54              type                empty;
55          }
56      }
```

- For the **bottom** patch (lines 42-45), we are using a **zeroGradient** boundary condition (we are just extrapolating the internal values to the boundary face).
- For the **front** and **back** patches (lines 47-55), we use an empty boundary condition. This boundary condition is used for 2D simulations. These two patches are normal to the direction where we assigned 1 cell (**Z** direction).
- At this point, if you take some time and compare the files *0/U* and *0/p* with the file *constant/polyMesh/boundary*, you will see that the name and type of each **primitive type** patch (the patch defined in *0*), is consistent with the **base type** patch (the patch defined in the file *constant/polyMesh/boundary*).

A simple validation case – Hagen-Poiseuille solution

The file *0/U*

```
19    internalField   uniform (0 0 0);
20
21    boundaryField
22    {
23        inlet
24        {
25            type            fixedValue;
26            value           uniform (1 0 0);
27        }
28
29        outlet
30        {
31          type          zeroGradient;
32        }
33
34        top
35        {
36            type            fixedValue;
37            value           uniform (0 0 0);
38        }
```

- We are using uniform initial conditions and the numerical value is **(0 0 0)** (keyword **internalField** in line 19).
- For the **inlet** patch (lines 23-27), we are using a **fixedValue** boundary condition with a numerical value equal to **(1 0 0)**
- For the **outlet** patch (lines 29-32), we are using a **zeroGradient** boundary condition (we are just extrapolating the internal values to the boundary face).
- The **top** patch is a no-slip wall (lines 34-38), therefore we impose a velocity of **(0 0 0)** at the wall.

A simple validation case – Hagen-Poiseuille solution

The file *0/U*

```
40        bottom
41        {
42            type            fixedValue;
43            value           uniform (0 0 0);
44        }
45
46        front
47        {
48            type            empty;
49        }
50
51        back
52        {
53            type            empty;
54        }
55    }
```

- The **bottom** patch is a no-slip wall (lines 40-44), therefore we impose a velocity of **(0 0 0)** at the wall.
- For the **front** and **back** patches (lines 46-54), we use an empty boundary condition. This boundary condition is used for 2D simulations. These two patches are normal to the direction where we assigned 1 cell (**Z** direction).
- At this point, if you take some time and compare the files *0/U* and *0/p* with the file *constant/polyMesh/boundary*, you will see that the name and type of each **primitive type** patch (the patch defined in *0*), is consistent with the **base type** patch (the patch defined in the file *constant/polyMesh/boundary*).

A simple validation case – Hagen-Poiseuille solution

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.

A simple validation case – Hagen-Poiseuille solution

The *controlDict* dictionary

```
17    application      icoFoam;
18
19    startFrom        startTime;
20
21    startTime        0;
22
23    stopAt           endTime;
24
25    endTime          20;
26
27    deltaT           0.05;
28
29    writeControl     runTime;
30
31    writeInterval    1;
32
33    purgeWrite       0;
34
35    writeFormat      ascii;
36
37    writePrecision   8;
38
39    writeCompression off;
40
41    timeFormat       general;
42
43    timePrecision    6;
44
45    runTimeModifiable true;
```

- This case starts from time 0 (**startTime**).
- It will run up to 20 seconds (**endTime**).
- The time step of the simulation is 0.05 seconds (**deltaT**).
- It will write the solution every 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**). It will only save eight digits in the output files.
- And as the option **runTimeModifiable** is on, we can modify all these entries while we are running the simulation.

A simple validation case – Hagen-Poiseuille solution

The `controlDict` dictionary

```
49      functions
50      {

            name_of_the_functionObject_dictionary
            {
                Dictionary with the functionObject entries
            }



204
207     };
```

- Let us take a look at the bottom of the `controlDict` dictionary file.
- Here we define **functionObjects**, which are functions that will do a computation while the simulation is running.
- We define the **functionObjects** in the sub-dictionary **functions** (line 49-207 in this case).
- Each **functionObject** we define, has its own name and its compulsory keywords and entries.
- In this case we are defining **functionObjects** to compute minimum and maximum values of the field variables, mass flow at the **inlet** and **outlet** patches, pressure average at the **inlet** patch, and maximum velocity at the **outlet** patch.
- In another variation of this case, we will use the output of the pressure average **functionObject** to set the numerical value of a pressure boundary condition at the **inlet** patch.
- The output of the maximum velocity **functionObject** will be used to plot the analytical solution (we can also use the `postProcess` utility to find this value).
- We are going to address **functionObjects** in details when we talk about post-processing.

A simple validation case – Hagen-Poiseuille solution

The *controlDict* dictionary

```
49      functions
50      {
51
54      minmaxdomain
55      {
56          type fieldMinMax;
57
58          functionObjectLibs ("libfieldFunctionObjects.so");
59
60          enabled true; //true or false
61
62          mode component;
63
64          writeControl timeStep;
65          writeInterval 1;
66
67          log true;
68
69          fields ( p U );
70      }
71
```

- **fieldMinMax functionObject**
  - This **functionObject** is used to compute the minimum and maximum values of the field variables.
  - The output of this **functionObject** is saved in ascii format in the file *fieldMinMax.dat* located in the directory

    postProcessing/minmaxdomian/0

A simple validation case – Hagen-Poiseuille solution

The *controlDict* dictionary

```
75      inMassFlow
76      {
77          type                surfaceRegion;
78          functionObjectLibs ("libfieldFunctionObjects.so");
79          enabled             true;
80
81          //writeControl      outputTime;
82          writeControl    timeStep;
83          writeInterval   1;
84
85          log                 true;
86
87          writeFields         false;
88
89          regionType          patch;
90          Name                inlet;
91
92          operation           sum;
93
94          fields
95          (
96              phi
97          );
98      }
```

- **faceSource functionObject**
  - This **functionObject** is used to compute the mass flow in a boundary patch.
  - In this case, we are sampling the patch **inlet**.
  - The output of this **functionObject** is saved in ascii format in the file *faceSource.dat* located in the directory

    postProcessing/inMassFlow/0

A simple validation case – Hagen-Poiseuille solution

The *controlDict* dictionary

```
102    outMassFlow
103    {
104        type            surfaceRegion;
105        functionObjectLibs ("libfieldFunctionObjects.so");
106        enabled         true;
107
108        //writeControl     outputTime;
109        writeControl    timeStep;
110        writeInterval   1;
111
112        log             true;
113
114        writeFields     false;
115
116        regionType      patch;
117        Name            outlet;
118
119        operation       sum;
120
121        fields
122        (
123            phi
124        );
125    }
```

- **faceSource functionObject**
  - This **functionObject** is used to compute the mass flow in a boundary patch.
  - In this case, we are sampling the patch **outlet**.
  - The output of this **functionObject** is saved in ascii format in the file *faceSource.dat* located in the directory

    `postProcessing/outMassFlow/0`

A simple validation case – Hagen-Poiseuille solution

The *controlDict* dictionary

```
130    inPre
131    {
132        type                surfaceRegion;
133        functionObjectLibs ("libfieldFunctionObjects.so");
134        enabled             true;
135
136        //writeControl      outputTime;
137        writeControl    timeStep;
138        writeInterval   1;
139
140        log                 true;
141
142        writeFields         false;
143
144        regionType          patch;
145        name                inlet;
146
147        operation           weightedAverage;
148
149        fields
150        (
151            phi
152            U
153            p
154        );
155    }
```

- **faceSource functionObject**
  - This **functionObject** is used to compute the weighted average in a boundary patch.
  - In this case, we are sampling the patch **inlet**.
  - The output of this **functionObject** is saved in ascii format in the file *faceSource.dat* located in the directory

    postProcessing/inPre/0

A simple validation case – Hagen-Poiseuille solution

The *controlDict* dictionary

```
179    outMax
180    {
181        type            surfaceRegion;
182        functionObjectLibs ("libfieldFunctionObjects.so");
183        enabled         true;
184
185        //writeControl      outputTime;
186        writeControl    timeStep;
187        writeInterval   1;
188
189        log             true;
190
191        writeFields     false;
192
193        regionType      patch;
194        name            outlet;
195
196        operation       max;
197
198        fields
199        (
200            U
201            p
202        );
203    }
204
207    };
```

- **faceSource functionObject**
  - This **functionObject** is used to compute the maximum value in a boundary patch.
  - In this case, we are sampling the patch **outlet**.
  - The output of this **functionObject** is saved in ascii format in the file *faceSource.dat* located in the directory

    postProcessing/outMax/0

  - Finally, remember that you can use the banana method to get a list of the different options available for each keyword.
  - You can also read the source code or the doxygen documentation.

A simple validation case – Hagen-Poiseuille solution

The *fvSchemes* dictionary

```
17    ddtSchemes
18    {
19        default         Euler;
20    }
21
22    gradSchemes
23    {
24        default         Gauss linear;
27        grad(p)         Gauss linear;
28    }
29
30    divSchemes
31    {
32        default         none;
33        div(phi,U)      Gauss linear;
37    }
38
39    laplacianSchemes
40    {
41        default         Gauss linear orthogonal;
44    }
45
46    interpolationSchemes
47    {
48        default         linear;
49    }
50
51    snGradSchemes
52    {
53        default         orthogonal;
56    }
```

- In this case, for time discretization (**ddtSchemes**) we are using the **Euler** method.
- For gradient discretization (**gradSchemes**) we are using the **Gauss linear** method.
- For the discretization of the convective terms (**divSchemes**) we are using **linear** interpolation method for the term **div(phi,U)**.
- For the discretization of the Laplacian (**laplacianSchemes** and **snGradSchemes**) we are using the **Gauss linear** method with **orthogonal** corrections.
- This method is second order accurate but oscillatory.
- Remember, at the end of the day we want a solution that is second order accurate.

A simple validation case – Hagen-Poiseuille solution

The *fvSolution* dictionary

```
17    solvers
18    {
19        p
20        {
27            solver          GAMG;
28            tolerance       1e-6;
29            relTol          0.01;
30            smoother        GaussSeidel;
31            nPreSweeps      0;
32            nPostSweeps     2;
33            cacheAgglomeration on;
34            agglomerator    faceAreaPair;
35            nCellsInCoarsestLevel 100;
36            mergeLevels     1;
37        }
38
39        pFinal
40        {
41            $p;
42            relTol         0;
43        }
44
45        U
46        {
53            solver         PBiCG;
54            preconditioner DILU;
55            tolerance      1e-08;
56            relTol         0;
57        }
58    }
59
60    PISO
61    {
62        nCorrectors      1;
63        nNonOrthogonalCorrectors 0;
66    }
```

- 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 solver will stop iterating when it meets any of the conditions).
- The entry **pFinal** refers to the final correction of the **PISO** loop. In this case, we are using a tighter convergence criteria in the last iteration. Notice that we are using macro expansion (**$p)** to copy the entries from the sub-dictionary **p**.
- To solve **U** we are using the linear solver **PBiCG** and **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.

A simple validation case – Hagen-Poiseuille solution

The *fvSolution* dictionary

```
17    solvers
18    {
19        p
20        {
27            solver          GAMG;
28            tolerance       1e-6;
29            relTol          0.01;
30            smoother        GaussSeidel;
31            nPreSweeps      0;
32            nPostSweeps     2;
33            cacheAgglomeration on;
34            agglomerator    faceAreaPair;
35            nCellsInCoarsestLevel 100;
36            mergeLevels     1;
37        }
38
39        pFinal
40        {
41            $p;
42            relTol         0;
43        }
44
45        U
46        {
53            solver         PBiCG;
54            preconditioner DILU;
55            tolerance      1e-08;
56            relTol         0;
57        }
58    }
59
60    PISO
61    {
62        nCorrectors      1;
63        nNonOrthogonalCorrectors 0;
66    }
```

- The **PISO** sub-dictionary contains entries related to the pressure-velocity coupling (in this case the **PISO** method).
- Hereafter we are doing only one 1 **PISO** corrector and no non-orthogonal corrections.
- 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**).

A simple validation case – Hagen-Poiseuille solution

The **`system`** directory

- In **`system`** directory you will find the following optional dictionary files:
  - *`decomposeParDict`*
  - *`modifyMeshDict`*
  - *`sampleDict`*

- *`decomposeParDict`* is read by the utility `decomposePar`. This dictionary file contains information related to the mesh partitioning. This is used when running in parallel.
- *`modifyMeshDict`* is read by the utility `modifyMesh`. This utility is used to manipulate mesh elements. This dictionary file contains information about the mesh manipulation operation we want to do.
- *`sampleDict`* is read by the utility `postProcess`. This utility sample field data (points, lines or surfaces). In this dictionary file we specify the sample location and the fields to sample. The sampled data can be plotted using gnuplot or Python.

A simple validation case – Hagen-Poiseuille solution

The *sampleDict* dictionary

```
17    setFormat raw;
18
19    setFormat raw;
20
22    interpolationScheme cellPoint;
24
26    fields
27    (
28        U
29        p
30    );
31
32    sets
33    (
34
35        s1
36        {
37            type            lineCell;
39            axis            x;
40            start           ( 0 0 0 );
41            end             ( 10 0 0);
42        }
43
45        s2
46        {
47            type            midPoint;
49            axis            y;
50            start           ( 9 -1 0 );
51            end             ( 9 1 0 );
52        }
53
54    );
```

- Let us visit again the *sampleDict* dictionary file.
- In this case we are sampling the field variables **U** and **p**.
- We are sampling in an horizontal line spanning from 0 to 10 (lines 35-42).
- We are sampling in a vertical line spanning from -1 to 1 (lines 45-52).
- If you want to sample in a different location feel free to add a new entry.

A simple validation case – Hagen-Poiseuille solution

Running the case

- You will find this tutorial in the directory **$PTOFC/101OF/laminar_pipe/case0**
- In the terminal window type:

```
1.  $> foamCleanTutorials
2.  $> blockMesh
3.  $> checkMesh
4.  $> icoFoam > log | tail –f log
5.  $> postProcess -func sampleDict -latestTime
6.  $> gnuplot gnuplot/gnuplot_script
7.  $> paraFoam
```

A simple validation case – Hagen-Poiseuille solution

Running the case

- In step 1 we clean the case directory. It is highly advisable to always start form a clean case directory.
- In step 2 we generate the mesh.
- In step 3 we check the mesh quality.
- In step 4 we run the simulation. Notice that we are redirecting the output to the a log file and at the same time we are showing the information on-the-fly.
- In step 5 we do some sampling only of the last saved solution.
- In step 6 we use a gnuplot script to plot the sampled values. Feel free to take a look at the script and to reuse it.
- Finally, in step 7 we visualize the solution.

A simple validation case – Hagen-Poiseuille solution

Let us use different boundary conditions

- Instead of using a fixed value for the velocity, let us use a fixed value for the pressure.
- You can use any pressure value, but as in the previous case we computed the average pressure at the inlet it seems wise to use this value.
- At this point, get the average pressure value from the ascii file (we hope you remember the location of the file), change the boundary conditions, and run the simulation.
- To run simulation proceed as in the previous case.
- At the end, compare both cases. You should get very similar results.
- If you are feeling lazy, this case is already setup in the directory

```
$PTOFC/101OF/laminar_pipe/case1
```

A simple validation case – Hagen-Poiseuille solution

The file *0/p*

- We only need to change the boundary conditions of the **inlet** patch.

```
inlet
{
    type                fixedValue;
    value               uniform 1.53103;
}
```

- Do you think of an alternative to the **fixedValue** boundary condition?

A simple validation case – Hagen-Poiseuille solution

The file *0/U*

- We only need to change the boundary conditions of the **inlet** patch.

```
inlet
{
    type                pressureNormalInletOutletVelocity;
    phi                 phi;
    rho                 rho;
    value               uniform (0 0 0);
}
```

- If you want to know what is behind this esoteric boundary condition, refer to the doxygen documentation or the source code.
- FYI, you can also use **zeroGradient**.

A simple validation case – Hagen-Poiseuille solution

Running with a steady state solver

- At Re = 100 nothing is happening. No vortex shedding, no detached flow, no flow instabilities, no turbulence, and no shock waves (this is kind of a boring case). Therefore is safe to say that this is a steady flow.
- In this case, we can use a steady solver. Steady solvers are way much faster than unsteady solvers but they violate a lot of principles, this is a trick that CFDers use to speed-up things. If you are happy with this approximation use steady solvers with no remorse.
- In an ideal world, steady solvers should converge in one iteration. But due to the non-linearities in the governing equations we need to proceed in an iterative way, until we satisfy a convergence criteria.
- Let us run this case using `simpleFoam` (which is an incompressible steady solver).
- As we are using a new solver we need to do some changes in the dictionaries files.
- This case is already setup in the directory **`$PTOFC/101OF/laminar_pipe/case2`**
- At this point, let us explore the case directory.

A simple validation case – Hagen-Poiseuille solution

- The following dictionary files remains unchanged:
  - *system/blockMeshDict*
  - *constant/polyMesh/boundary*
  - *0/U*
  - *0/p*
- FYI, we are using the same setup as in case **`case2`**
- New dictionary files
  - *turbulenceProperties*
- The solver `simpleFoam` can be used for laminar and turbulent flows.
- The following dictionaries need to be modified:
  - *transportProperties*
  - *controlDict*
  - *fvSchemes*
  - *fvSolution*

A simple validation case – Hagen-Poiseuille solution

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).
- As we are not interested in modeling turbulence, this dictionary should read as follows,

```
17    simulationType    laminar;
```

A simple validation case – Hagen-Poiseuille solution

The *transportProperties* dictionary file

- In this file we define the transport model and the kinematic viscosity (**nu**).

```
16    transportModel  Newtonian;
17
18    nu              nu [ 0 2 -1 0 0 0 0 ] 0.01;
```

- The file *transportProperties* used with the solver icoFoam, does not require the keyword **transportModel**. The solver icoFoam only uses the Newtonian model.

A simple validation case – Hagen-Poiseuille solution

The *controlDict* dictionary

```
17    application       simpleFoam;
18
19    startFrom         startTime;
20
21    startTime         0;
22
23    stopAt            endTime;
24
25    endTime           1000;
26
27    deltaT            1;
28
29    writeControl      runTime;
30
31    writeInterval     10;
32
33    purgeWrite        0;
34
35    writeFormat       ascii;
36
37    writePrecision    8;
38
39    writeCompression off;
40
41    timeFormat        general;
42
43    timePrecision     6;
44
45    runTimeModifiable true;
```

- As this is a steady solver it does not make any sense setting the time step.
- The time step is only used to advanced the solution (iterate) and to save the solution.
- The keyword **endTime** refers to the maximum number of iterations.

A simple validation case – Hagen-Poiseuille solution

The *fvSchemes* dictionary

```
17   ddtSchemes
18   {
19       default         steadyState;
20   }
21
22   gradSchemes
23   {
24       default         Gauss linear;
27       grad(p)         Gauss linear;
28   }
29
30   divSchemes
31   {
32       default         none;
33       div(phi,U)      bounded Gauss linear;
38      div((nuEff*dev2(T(grad(U))))) Gauss linear;
39   }
40
41   laplacianSchemes
42   {
43       default         Gauss linear orthogonal;
46   }
47
48   interpolationSchemes
49   {
50       default         linear;
51   }
52
53   snGradSchemes
54   {
55       default         orthogonal;
58   }
```

- These are the changes introduced in the dictionary:
  - Time discretization (**ddtSchemes**), is **steadyState**.
  - For the discretization of the convective terms (**divSchemes**) we are using a **bounded linear** interpolation method for the term **div(phi,U)**
  - We added the term **div((nuEff*dev2(T(grad(U))))**. This term is related to the turbulence formulation. We must define it even if we are using the laminar model.

A simple validation case – Hagen-Poiseuille solution

The *fvSolution* dictionary

```
17    solvers
18    {
19        p
20        {
27            solver          GAMG;
28            tolerance       1e-6;
29            relTol          0.01;
30            smoother        GaussSeidel;
31            nPreSweeps      0;
32            nPostSweeps     2;
33            cacheAgglomeration on;
34            agglomerator    faceAreaPair;
35            nCellsInCoarsestLevel 100;
36            mergeLevels     1;
37        }
38
39        U
40        {
47            solver          PBiCG;
48            preconditioner  DILU;
49            tolerance       1e-08;
50            relTol          0;
51        }
52    }
```

- 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 solver will stop iterating when it meets any of the conditions).
- To solve **U** we are using the solver **PBiCG** 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).
- FYI, solving for the velocity is relative inexpensive, whereas solving for the pressure is expensive.

A simple validation case – Hagen-Poiseuille solution

The *fvSolution* dictionary

```
54    SIMPLE
55    {
56        nNonOrthogonalCorrectors 1;
61
62        residualControl
63        {
64            p     1e-4;
65            U     1e-4;
69        }
70    }
71
73    relaxationFactors
74    {
75        fields
76        {
77            P     0.3;
78        }
79        equations
80        {
81            U     0.7;
84        }
85    }
```

- The **SIMPLE** sub-dictionary contains entries related to the pressure-velocity coupling (in this case the **SIMPLE** method).
- Hereafter we are doing one non orthogonal correction.
- In the sub-dictionary **residualControl** we set the convergence criteria for each field variable. The solver will stop if it reach this criterion or the maximum number of iterations (**endTime**).
- In the sub-dictionary **relaxationFactors** we set the under-relaxation coefficients. The under-relaxation factors (URF) controls how fast the solution change between iterations. Choosing the optimal URF requires a lot experience. It is wise to stick to the commonly used values.

p	**0.3;**
U	**0.7;**
k	**0.7;**
omega	**0.7;**
epsilon	**0.7;**

A simple validation case – Hagen-Poiseuille solution

Running the case

- You will find this tutorial in the directory **`$PTOFC/101OF/laminar_pipe/case2`**
- In the terminal window type:

```
1.  $> foamCleanTutorials
2.  $> blockMesh
3.  $> checkMesh
4.  $> simpleFoam > log | tail -f log
5.  $> postProcess -func sampleDict -latestTime
6.  $> gnuplot gnuplot/gnuplot_script
7.  $> paraFoam
```

A simple validation case – Hagen-Poiseuille solution

Running the case

- In step 1 we clean the case directory. It is highly advisable to always start form a clean case directory.
- In step 2 we generate the mesh.
- In step 3 we check the mesh quality.
- In step 4 we run the simulation. Notice that we are redirecting the output to the a log file and at the same time we are showing the information on-the-fly.
- In step 5 we do some sampling only of the last saved solution.
- In step 6 we use a gnuplot script to plot the sampled values. In this case, you will need to adapt this script to get the sampled data from the right directory.
- Finally, in step 7 we visualize the solution.
- Compare this solution with the solution of the case **`case0`**

A simple validation case – Hagen-Poiseuille solution

What about mesh quality?

- So far we have worked with perfect meshes, that is, meshes with non-orthogonality and skewness close to zero.
- But this is the exception rather than the rule.
- Getting a solution in this kind of meshes is quite easy.

```
Checking geometry...
    Overall domain bounding box (0 -0.5 0) (10 0.5 0.1)
    Mesh has 2 geometric (non-empty/wedge) directions (1 1 0)
    Mesh has 2 solution (non-empty) directions (1 1 0)
    All edges aligned with or perpendicular to non-empty directions.
    Boundary openness (7.8140697e-20 1.4221607e-17 5.4393739e-16) OK.
    Max cell openness = 8.6736174e-17 OK.
    Max aspect ratio = 1 OK.
    Minimum face area = 0.01. Maximum face area = 0.01.  Face area magnitudes OK.
    Min volume = 0.001. Max volume = 0.001.  Total volume = 1.  Cell volumes OK.
    Mesh non-orthogonality Max: 0 average: 0
    Non-orthogonality check OK.
    Face pyramids OK.
    Max skewness = 1.0658141e-13 OK.
    Coupled point location match (average 0) OK.

Mesh OK.
```

Non-orthogonality

Skewness

A simple validation case – Hagen-Poiseuille solution

What about mesh quality?

- Industrial meshes are far from being perfect.
- Mesh quality highly affect solution accuracy, stability, and convergence rate.
- To take into account mesh quality issues, we need to adjust the numerical method. We will deal with this during the FVM lecture.

```
Checking geometry...
    Overall domain bounding box (0 -0.5 0) (10 0.5 0.1)
    Mesh has 2 geometric (non-empty/wedge) directions (1 1 0)
    Mesh has 2 solution (non-empty) directions (1 1 0)
    All edges aligned with or perpendicular to non-empty directions.
    Boundary openness (7.8140697e-20 1.4221607e-17 5.539394e-16) OK.
    Max cell openness = 9.3768837e-17 OK.
    Max aspect ratio = 1.98 OK.
    Minimum face area = 0.00085. Maximum face area = 0.02154739.  Face area magnitudes OK.
    Min volume = 8.5e-05. Max volume = 0.001915.  Total volume = 1.  Cell volumes OK.
    Mesh non-orthogonality Max: 86.473612 average: 2.5674993
   *Number of severely non-orthogonal (> 70 degrees) faces: 1.
    Non-orthogonality check OK.
  <<Writing 1 non-orthogonal faces to set nonOrthoFaces
 ***Error in face pyramids: 2 faces are incorrectly oriented.
  <<Writing 2 faces with incorrect orientation to set wrongOrientedFaces
 ***Max skewness = 11.305066, 1 highly skew faces detected which may impair the quality of the results
  <<Writing 1 skew faces to set skewFaces
    Coupled point location match (average 0) OK.

Failed 2 mesh checks.
```

Too high non-orthogonality
Acceptable values are less than 80

Failed sets can be
visualized in paraFoam

Too high skewness
Acceptable values are less than 6

This does not mean that you can
not run the simulation