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code_saturne documentation

**code_saturne version 7.0 tutorial:
Shear Driven Cavity Flow**

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Part I

Introduction

1 Introduction

1.1 Tutorial Components

This tutorial makes use of:

- The SALOME [\[1\]](#) platform for geometry generation, meshing, and post-processing
- code_saturne [\[2\]](#), [\[3\]](#) for CFD calculations. Some tips are added to introduce you to **CFDStudy** on SALOME platform.
- Reference [\[4\]](#) for comparison with published results

Note that SALOME platform, if it includes the module CFDStudy (code_saturne integrated inside SALOME), is named SALOME _CFD. To work through this tutorial you don't need a computer on which SALOME _CFD is installed or on which you can run a SALOME _CFD installer. Alternatively, SALOME and code_saturne can be installed side by side in this order, allowing to specify a salome installation at code_saturne configuration step.

Important: Keep in mind that CFDStudy is just an additional module allowing users to keep one window opened, to navigate in and switch modules based on their needs. The aim is to provide an interface including multiple modules.

1.2 Tutorial Structure

This tutorial is made of two sections:

- Section [II](#) describes all the procedures required to get along with setting up CFD simulations using SALOME from code download to case creation.
- Section [III](#) illustrates setting up, running, and analysing a CFD simulation entirely with code_saturne, using the laminar, Shear Driven Cavity as an example. This case is simple but contains enough physics to make it interesting and relevant to practical problems.

If you are already familiar with setting up CFD simulations with SALOME, you may skip Section [II](#) and go directly to Section [III](#).

Part II

Setting up

1 Setting up

The first part of the tutorial is designed to explain the preliminary steps to setup an end-to-end CFD simulation using code_saturne and SALOME applications.

1.1 What you will learn

In the first part of the tutorial, you will learn:

- How code_saturne and SALOME may be combined in SALOME _CFD for end-to-end CFD analyses, from CAD generation to post-processing of CFD results
- How to access and download code_saturne and SALOME
- How to install SALOME and code_saturne within the CFDStudy module of SALOME
- How to set up a code_saturne case with CFDStudy

1.2 Using SALOME _CFD for End-to-End Simulations

code_saturne is a general, 3D CFD solver which can be applied to a large variety of problems involving fluid flow and heat transfer. The code_saturne Graphical User Interface (GUI) can be used on its own to define CFD cases, and to run them when a mesh is already available. It has also been integrated as a module called CFDStudy in the SALOME open-source host platform, where it links with other modules to provide a single, user-friendly, graphical environment for end-to-end CFD analyses:

- **Shaper:** CAD module
 - Geometry and computational domain definition
- **Mesh:** Meshing module
 - Surface and volume meshing of the computational domain and defining boundaries
- **CFDStudy:** CFD module
 - Set up and run code_saturne CFD calculations
- **Paravis:** Post-processing module
 - Visualisation and analysis with Paraview [5]

The set-up and the use of the different SALOME modules studies are described throughout different tutorials, starting with how to initiate a study with SALOME platform using CFDStudy.

1.3 Installing SALOME _CFD

The quickest way to get started is to retrieve a SALOME _CFD installer from SALOME website: www.salome-platform.org/contributions/edf_products. Then install SALOME _CFD by executing the installer in a terminal. For EDF collaborators, please follow this link : <https://salome.der.edf.fr/telecharger>

Alternatively, each application, code_saturne and SALOME, can be installed separately with an option allowing to integrate code_saturne inside Salome. Access to the applications is provided through their respective, dedicated internet sites. Install utilities, installation instructions, environment variables setup for Linux installations, and code documentation including user manuals can also be downloaded from the sites.

To integrate the code_saturne and the CFDStudy module in SALOME, SALOME must be installed first, followed by code_saturne:

1. SALOME

SALOME can be downloaded from the website: www.salome-platform.org or via <https://salome.der.edf.fr/telecharger> for EDF collaborators.

Complete versions come with the source and binary files and interactive installation procedures.

2. code_saturne and CFDStudy module

code_saturne can be downloaded from the website: www.code-saturne.org

The code is packaged with all its libraries and the installer, which can also be downloaded from the same site, makes the installation process fully automatic. However, external, required packages, such as Python, are not part of the code_saturne package and must be acquired from their respective publishers and installed separately. As part of the installation process, the code_saturne installer will check for their availability and issue notifications if they are not found.

To enable the CFDStudy module, the `--with-salome` flag must be added as a parameter to the `configure` command. The flag must point to the path of your SALOME application.

For example: `--with-salome=/opt/salome_9.7.0`.

Additional information can be found in the installation guide of code_saturne available on the code_saturne website.

1.4 Getting Started with End-to-End CFD Simulation

From now on, all steps are to be performed inside SALOME.

The process of creating the required code_saturne directory and file structures is described first, followed by an example for the Shear Driven Cavity Flow case.

File Structure

code_saturne makes use of a pre-set directory structure to access and save input and output files. Simulations are organised in terms of studies and cases. Conceptually, a study contains a series of cases which all rely on the same geometry. The cases represent different instances of simulations for this common geometry, for example for different operating conditions. The pre-set code_saturne directory structure can be easily created either using code_saturne GUI (Graphic User Interface) either via the Terminal or using SALOME CFDStudy module GUI.

Via code_saturne GUI First open code_saturne GUI

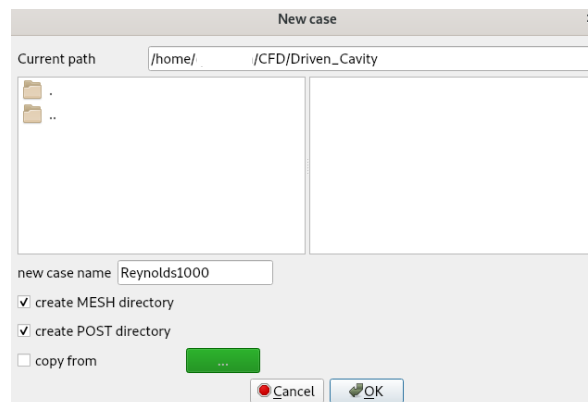


Figure II.1: New case creation with code_saturne GUI

Via the Terminal Make sure to be in the proper directory.

```
$cd 'directory path'
$code_saturne create -s Driven.Cavity -c Reynolds1000
```

Via SALOME To set up a study and a case, first open SALOME Graphical User Interface (GUI) by typing the command:

```
$ salome
```

in your terminal. This will start the SALOME platform with the CFDStudy module enabled.

Then, activate CFDStudy, either by selecting it in the module chooser in SALOME's top tool bar or by clicking on its icon (Figure II.2).

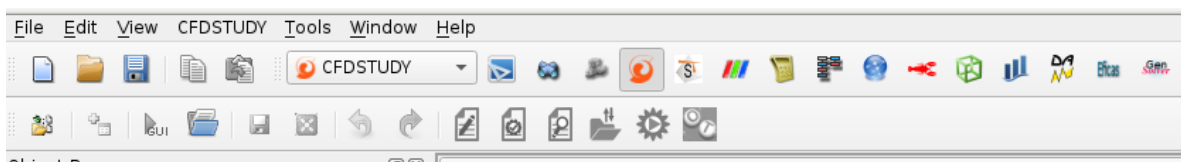


Figure II.2: Opening CFDStudy module

Enable **CFDSTUDY** toolbar, if it does not appear, in **View >> Toolbars >> CFDSTUDY**. In the toolbar or in the **CFDSTUDY** menu, click on **Choose an existing CFD study or Create**. The study and case creation panel will then pop up (Figure II.3).

 A screenshot of the 'code_saturne Study and Case Specification' dialog box. The dialog has a light gray background. At the top, there are two checkboxes: 'Load existing study or case' (unchecked) and 'Create study' (checked). Below these are two text input fields: 'Study/Case location' with the value '/home/jo680ben' and 'Study/Case name' with the value 'EXAMPLE_STUDY'. Under the heading 'Cases', there is a text input field containing 'CASE1'. Below this, there are two radio buttons: 'NEPTUNE_CFD' (unselected) and 'Code_Saturne' (selected). At the bottom, there are two more checkboxes: 'Copy from existing case' (unchecked) and 'Coupling with Syrthes' (unchecked). At the very bottom right are 'Cancel' and 'OK' buttons.

Figure II.3: code_saturne Study and Case Specification. Here a study called EXAMPLE_STUDY, containing CASE1, is created

In the panel, choose where you want the study to be stored on your computer and enter the names of the study and the first case. Further cases can be added to any study at a later stage. Press **OK** to create the study and the case. The entire directory structure required by code_saturne will then be created and the directory tree for the study and case will become visible in the Object Browser, as shown in Figure II.4.

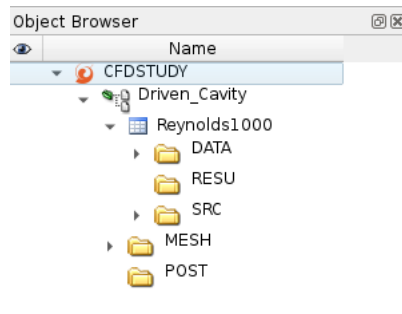


Figure II.4: Case directory and file structure.

Example: Creating the *Shear Driven Cavity Flow* Study within SALOME and CFDStudy module

Follow the steps described in 1.4 to open CFDStudy and create a new study.

Then select the path where the study directory will be created and name the study **Driven_Cavity**. In the **Case(s)** field enter the case name **Reynolds1000** as shown in Figure II.5.

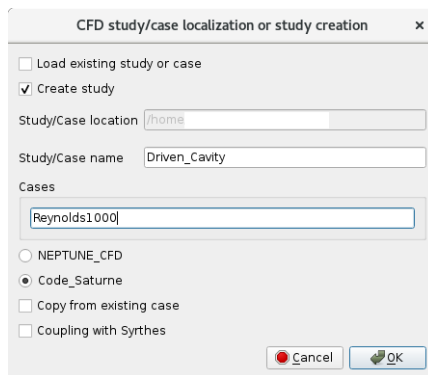


Figure II.5: Specifying the **Shear Driven Cavity Flow** Study and **Reynolds1000** Case

The whole directory structure of code_saturne is generated and can be visualized in the Object Browser tab (Figure II.6).

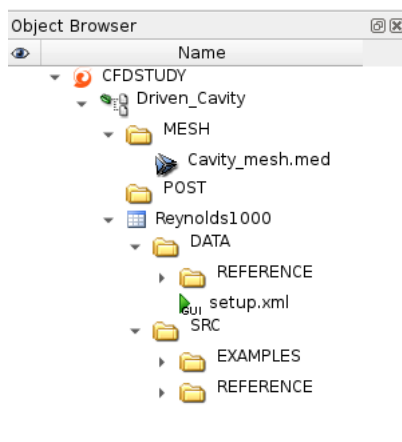












Figure II.6: **Shear Driven Cavity Flow** Study and **Reynolds1000** Case file structure

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The case is then ready to be set up, as described in [3.1](#).

The meaning of the different directories and files is recalled here briefly. For detailed information, please refer to the code_saturne user manual [\[3\]](#).

-  **DATA** directory
 -  **REFERENCE** directory
 - ▷ Tabulated thermophysical properties for chemical species and atmospheric properties
 - ▷ **cs_user_scripts.py** file
 - ↳ Python file in which users can modify code_saturne parameters and settings
 - **code_saturne** file
 - ▷ Shell file pointing to the code_saturne GUI executable
-  **RESU** directory
 - Initially empty, it will contain the results files and code_saturne outputs of each code_saturne run, organised in chronological order
-  **SRC** directory
 - User coding source files
 -  **REFERENCE** directory
 - ▷ Templates for all the available user coding files
 -  **EXAMPLES** directory
 - ▷ Practical examples of implementation of user coding for different purposes

Initially, the  **MESH** and  **POST** directories are both empty. By default when run from a case directory, code_saturne is set up to look for the mesh file in the  **MESH** directory. The  **POST** directory could contain post-processing routines if required.

Part III

Driven Cavity Flow Case

1 General description

In the second part of the tutorial, the preparation, simulation and analysis of the [Reynolds1000](#) case of the [DrivenCavity](#) study is described, from the construction of the computational domain and mesh to the preparation, running and post-processing of the CFD simulation. All the following steps in this second part are presented using SALOME module for geometry and mesh creation then using .

1.1 What You Will Learn

Through this tutorial, you will learn how to perform an end-to-end CFD simulation using code_saturne [2, 3] with the SALOME [1] platform, from geometry and meshing creation to the computation and post-treatment phases. Specifically, you will:

- Create a computational domain with SALOME using available shapes and groups
- Create an hexahedral mesh with different mesh refinements in the X , Y and Z directions with SALOME
- Setup a steady-state, viscous, laminar, isothermal, constant properties fluid CFD simulation with non-slip walls, a moving wall, and symmetry planes with code_saturne
- Control and run the code_saturne simulation
- Examine the code_saturne output and results files, including data along specified profiles and at monitoring points
- Analyse and visualise the results with SALOME ParaVis module

1.2 Case Description

A viscous fluid is contained in a box, or cavity. All the walls of the cavity are stationary, but for one wall which is sliding in its plane and sets the fluid in motion inside the box through entrainment. This is a well-know academic case for which published results are available [4].

For the purpose of this example, the cavity is rectangular, two-dimensional, and the top wall of the cavity slides from left to right, as illustrated in Figure III.1 below.

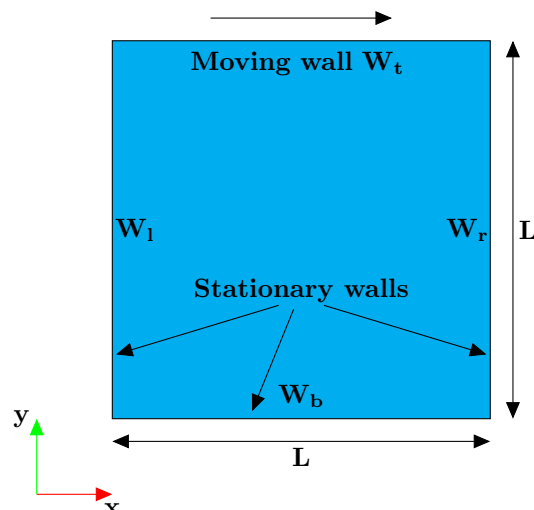


Figure III.1: Schematic of the 2D Lid Driven Cavity.

Geometry

The cavity is a square of length $L = 1.0 \text{ m}$.

Fluid Properties

The fluid is given the properties listed in Table III.1 below:

Property	Value	Units
Density (ρ)	1.0	kg/m^3
Viscosity (μ)	10^{-3}	$Pa.s$

Table III.1: Fluid Properties.

Boundary Conditions

The problem is considered to be isothermal and the domain is fully enclosed by impermeable, non-slip walls. This means that, exactly at the surface of the walls, the fluid inside the box attaches to the walls and has exactly the same velocity as the walls. Therefore, the problem is fully defined by specifying the velocity of the walls (Table III.2). The side and bottom walls are stationary. The top wall slides in the positive X direction at a speed of 1.0 m.s^{-1} .

Surface	Velocity component	
	$V_x \text{ (m/s)}$	$V_y \text{ (m/s)}$
W_l	0.0	0.0
W_b	0.0	0.0
W_r	0.0	0.0
W_t	1.0	0.0

Table III.2: Wall velocities.

Flow Regime

The flow Reynolds number is evaluated to determine whether the flow is in the laminar or turbulent regime. The Reynolds number is calculated based on the lid velocity, the box dimensions, and the fluid properties.

For this case, the fluid properties and lid velocity have been chosen so that $Re = \frac{\rho \cdot U \cdot L}{\mu} = 1000$, indicating that the problem is in the laminar flow regime.

1.3 Creating the code_saturne case

The **DrivenCavity** study and **Reynolds1000** case are created by following the instructions in section II of this tutorial.

The next paragraphs describe how to setup and run the lid driven cavity simulations for a flow Reynolds number of 1000.

2 Creating the Computational Domain within SALOME

First you need to create the geometry of the cavity which defines the bounds of the computational domain and then mesh this domain. Installation of this tool is described in section II.

code_saturne is a 3D code and, therefore, the computational domain will be created as a 3D box, aligned with the X , Y , and Z directions. However, as we are only interested in 2D modelling and the flow motion in the $X - Y$ plane, the box will be designed to be thin and contain only one computational cell in the Z direction.

2.1 Geometry

Once the CFD case structure is created, the current SALOME file is saved by accessing **File** > **Save**. For this tutorial, we choose the file name **Cavity** (Figure III.2). The file **Cavity.hdf** will be created in directory **Driven_Cavity**.

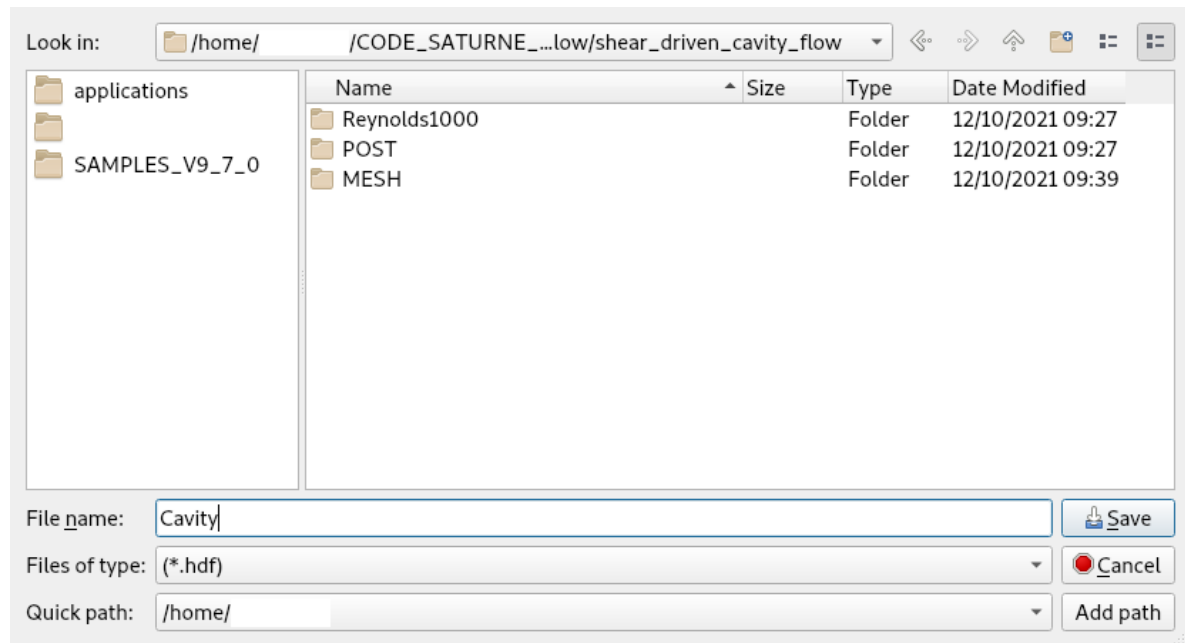



Figure III.2: Saving the SALOME file

Important: It is advisable to save the file at regular intervals when preparing a case, preferably, before and following all significant modifications. That way your latest work is preserved and, should mistakes happen, it is always possible to exit SALOME and restart it from the latest saved file.

As SALOME is an integrated interface to different capabilities: CAD, meshing, visualisation, the next step is to access the **Geometry** module of the program in order to start building the shape of the computational domain.

In the main menu bar, either click on the  icon or choose **Shaper** from the drop-down module menu as shown in Figure III.3 below.

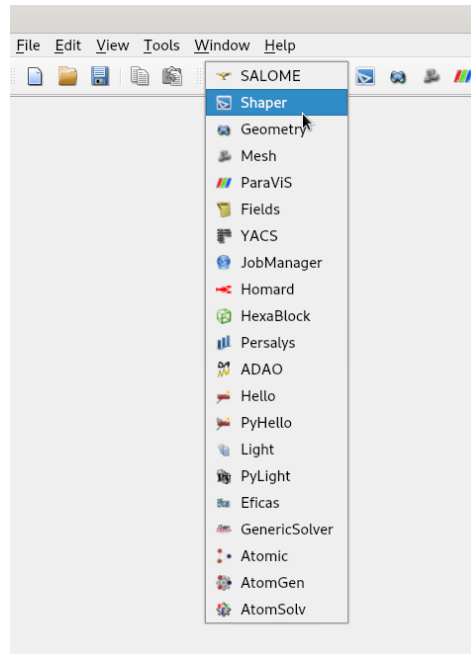



Figure III.3: Selecting **Geometry** in the module chooser.

The **Shaper** menu then becomes available in the top bar and the **OCC scene viewer** opens in the right hand side, where the geometry objects can be visualised and manipulated. The scene viewer comes with its own set of 3D-viewing menus to control the display and perform operations such as panning in and out, and rotating and moving the object in the scene.

The **Shaper** module of SALOME makes it possible to build bespoke objects from scratch from constituting elements such as vertices, edges and faces, or from pre-set generic shapes.

In this instance, we use the latter, more direct method and create the cubic cavity shape by selecting: **Part** > **New Part**. Alternatively, use the  icon short-cut on the menu bar.

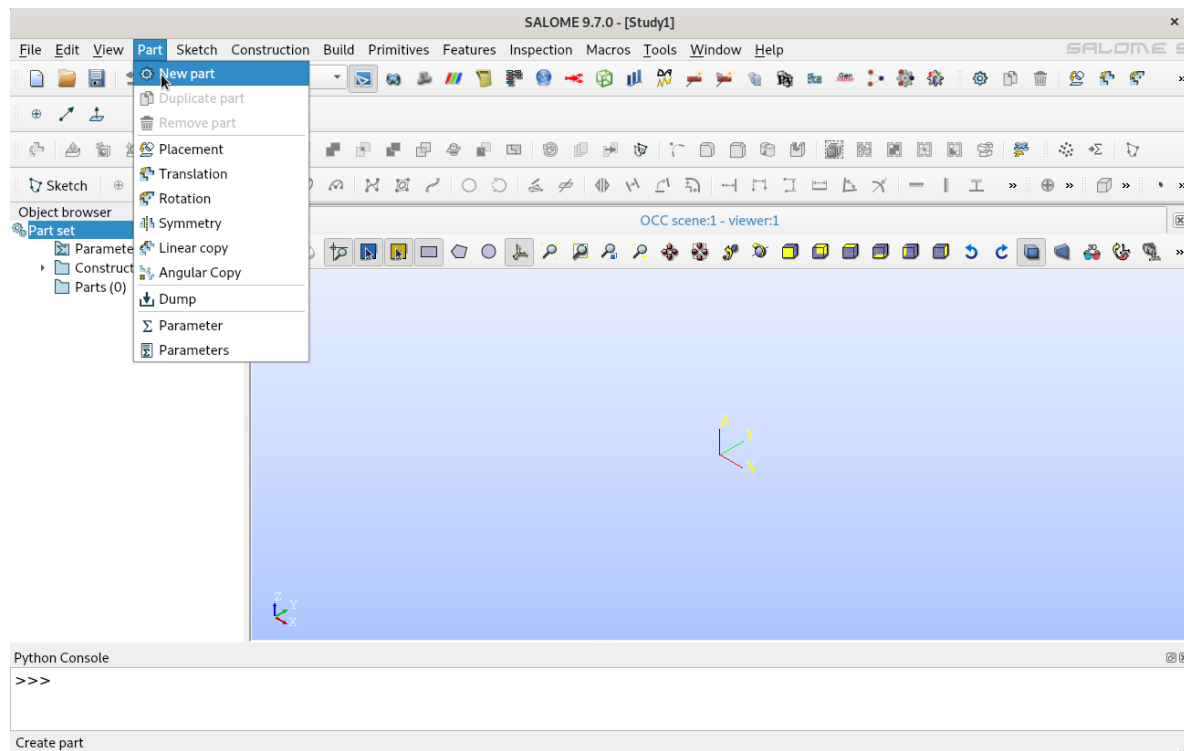




Figure III.4: New Part Creation

Then you can sketch a new wireframe by clicking on sketch button  located in the upper left of window and draw a rectangular shape - 1.00(m) x 1.00(m) - using Rectangle function  as follows :

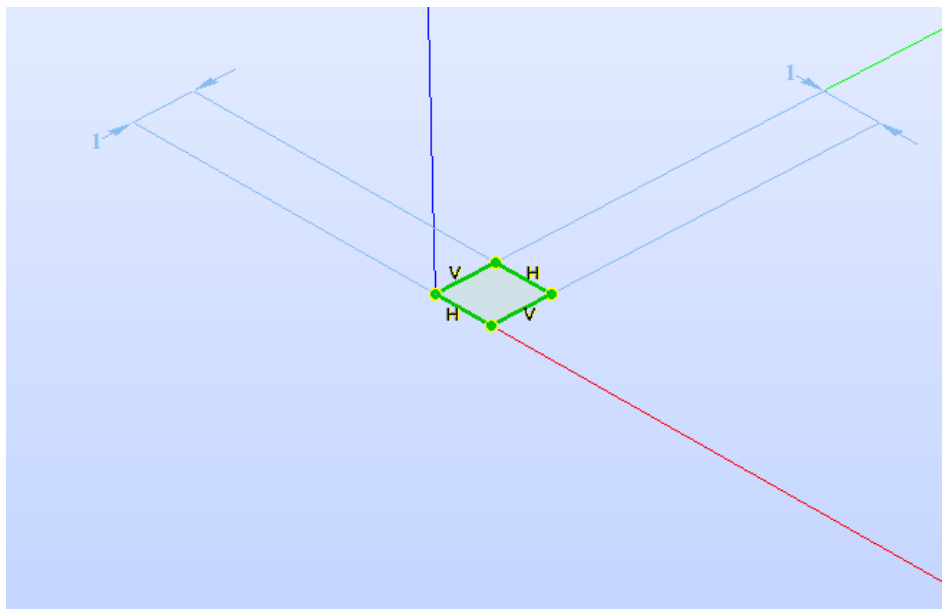


Figure III.5: Wireframe (top) and Shading (bottom) display modes.

To extrude the surface select extrusion icon then the face previously created and type 0.01(m) as follows :

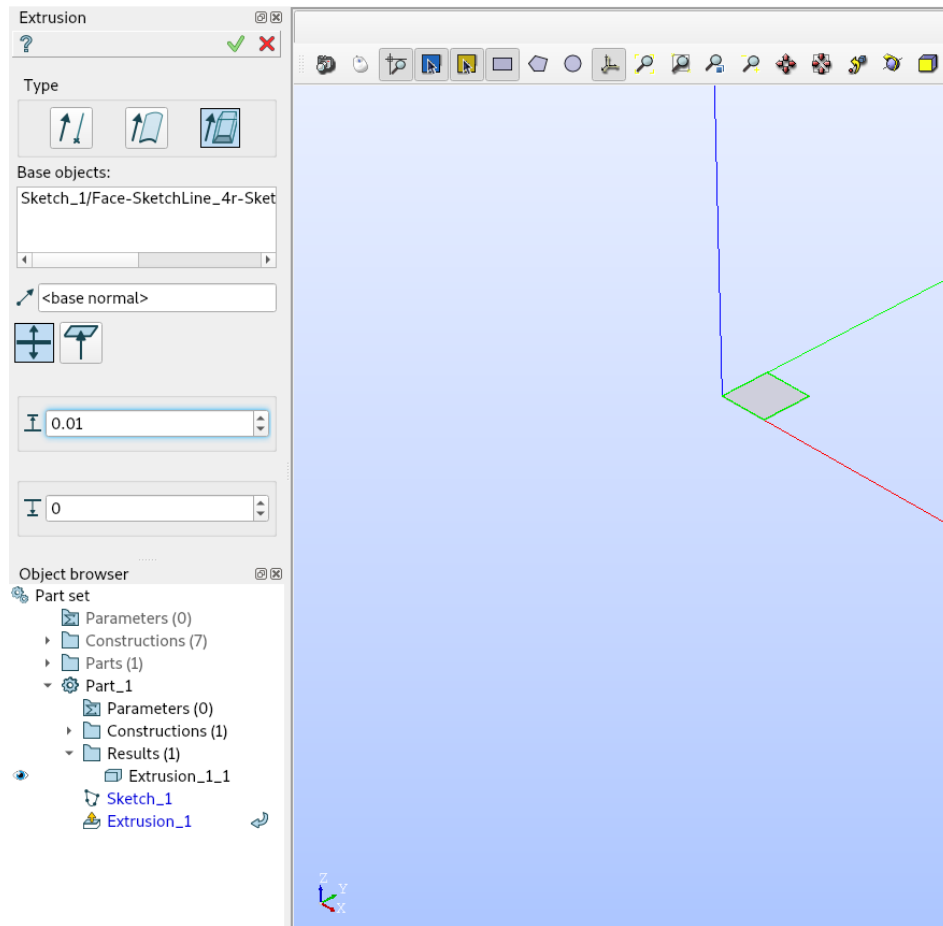


Figure III.6: New Part Extrusion

At this point, the cavity object is complete and could be meshed straight away. However, since the box has been created as a whole entity it would then neither be possible in the mesher to specify different meshing characteristics for the X , Y and Z directions nor to identify the 6 external surfaces as boundaries for the code_saturne calculations. Before meshing, it is then necessary to create and identify these elements. In the next step, you will create **Edges Groups** and **Faces Groups** by manually selecting them.

In order to create a group you need to click on Group icon under Features Tab and select planes and or edges you need for each wished group.

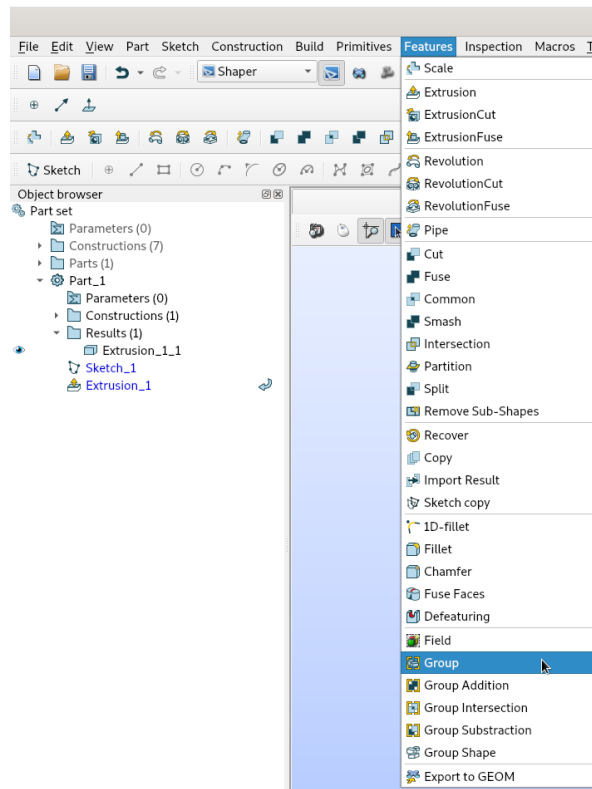


Figure III.7: New group

You should create 4 groups as follows:

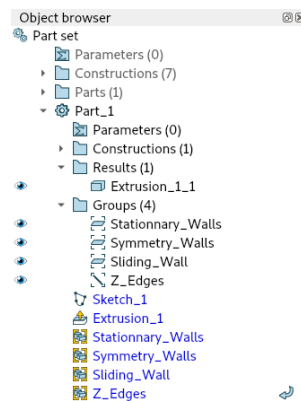



Figure III.8: Groups

For each of these groups you must select one or multiple objects referring to [III.1](#). To do so, you can use the Maj key on your keyboard and click left on the selected object. Stationnary_Walls should include 3 walls, Symmetry_Walls should include 2 Walls, Sliding_Wall should include 1 Wall and Z_Edges should include 4 edges following Z axis.

Part_1 is now ready to be meshed. Save the file and proceed to Meshing.

2.2 Meshing

Switch to the  meshing module, which opens the **VTK scene viewer** as shown in Figure III.9 below. In this view, the background colour has been changed to white similarly to the **OCC scene viewer** for the **Geometry**, by right clicking in the viewer and accessing **Change background ...**.

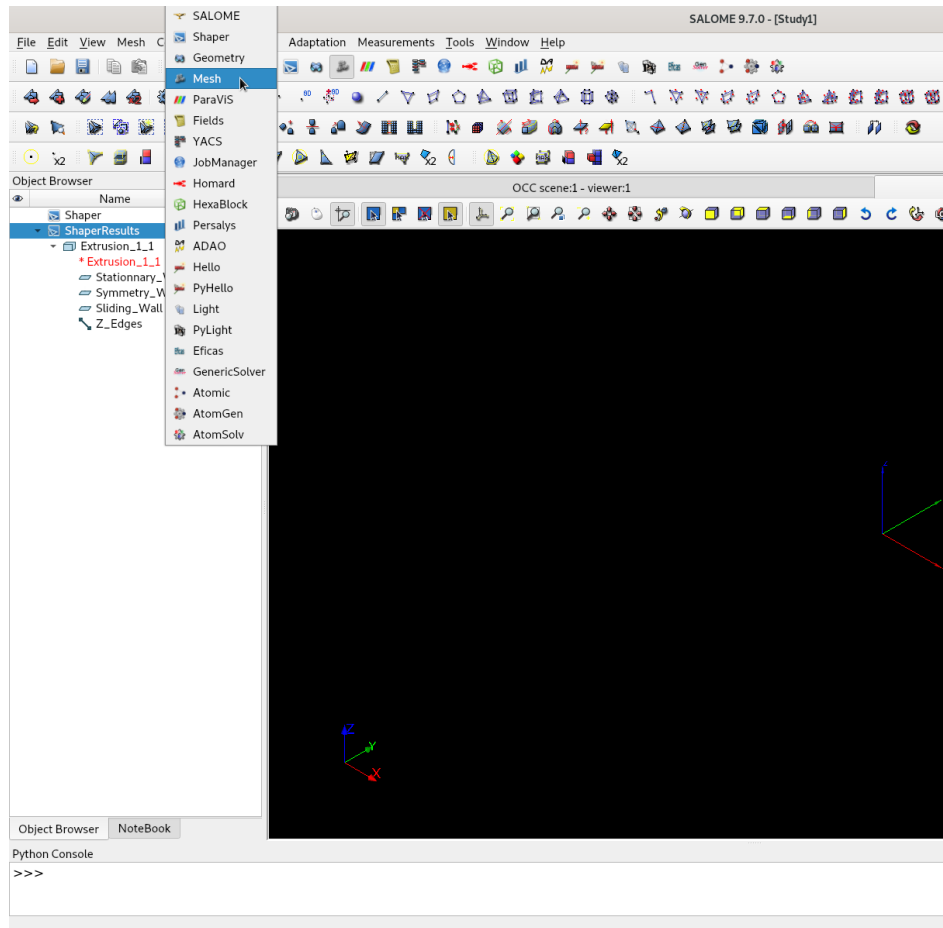


Figure III.9: Switching to the **Mesh** module.

Similarly to the earlier creation of the geometry object **Cavity** in the **Geometry** module, a **Cavity_mesh** mesh object is created first by selecting **Mesh** > **Create mesh** in the main menu bar.

As shown in Figure III.10 below, in the **Create mesh** pop-up menu, type **Cavity_mesh** for the **Name** and select **Cavity** as the **Geometry** object by left clicking on it in the Object Browser.

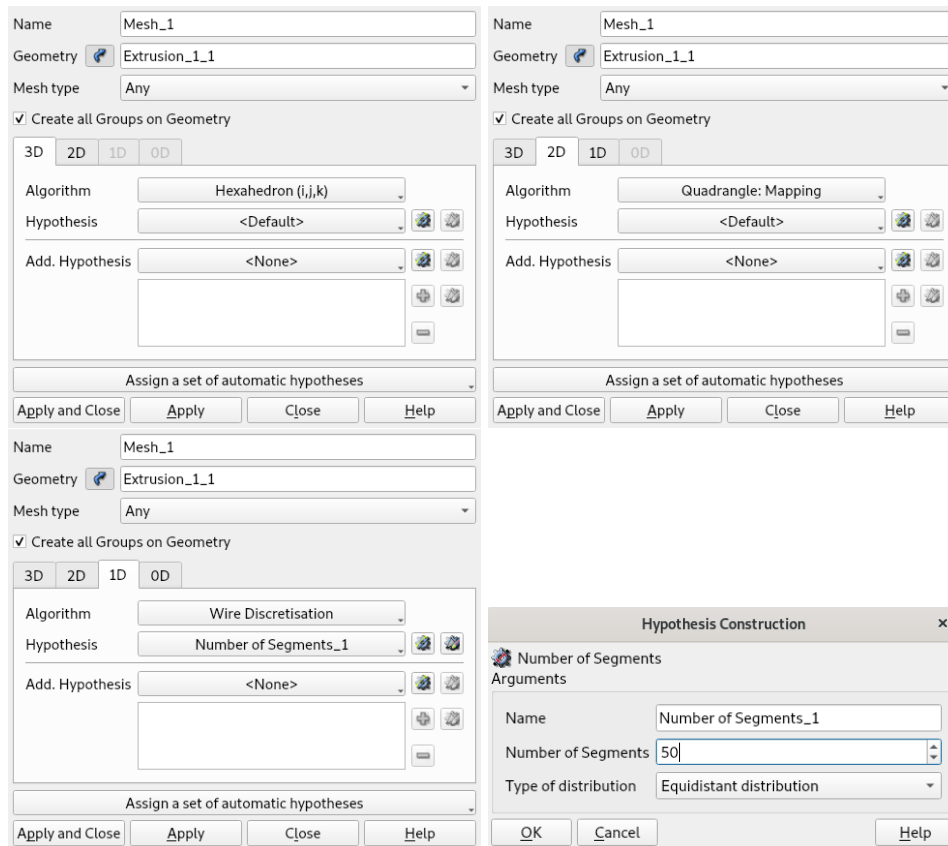



Figure III.10: 3D, 2D and 1D Meshing parameters

The main mesh object holds the global characteristics of the Cavity mesh.

For the volume, in the **3D** tab choose **Hexahedron (i,j,k)**. All the (external) surfaces of the Cavity will be meshed similarly, therefore a global setup is applied for the entire mesh via this pop-up menu by clicking on the **2D** tab and selecting **Quadrangle: Mapping**. These two selections will result in a block-structured mesh, with an (i, j, k) matrix structure. This requires identical discretisations along all the edges aligned along the same directions. If we wanted the discretisation to be the same along all the directions, for example 50 sub-divisions along the X , Y , and Z edges, the **1D** tab could be selected and this unique discretisation specified. However, here we need to be able, at least, to specify the Z direction independently of the two others to create a 3D domain which is only one cell deep. Therefore, Z edges discretisations will be specified separately using **sub-meshes**. Press **Apply and Close** before defining the **sub-meshes**.

The sub-mesh defining the meshing characteristics in the Z direction is specified first.

Right-click on **Cavity_mesh** in the Object Selector and select **Create sub-mesh**. Alternatively, with **Cavity_mesh** selected (highlighted) in the Object Browser, the sub-meshes can be created from **Mesh** or the short-cut icon  in the main menu bar. This activates the **Create sub-mesh** pop-up menu in the **VTK scene viewer** as shown in Figure III.11 below.

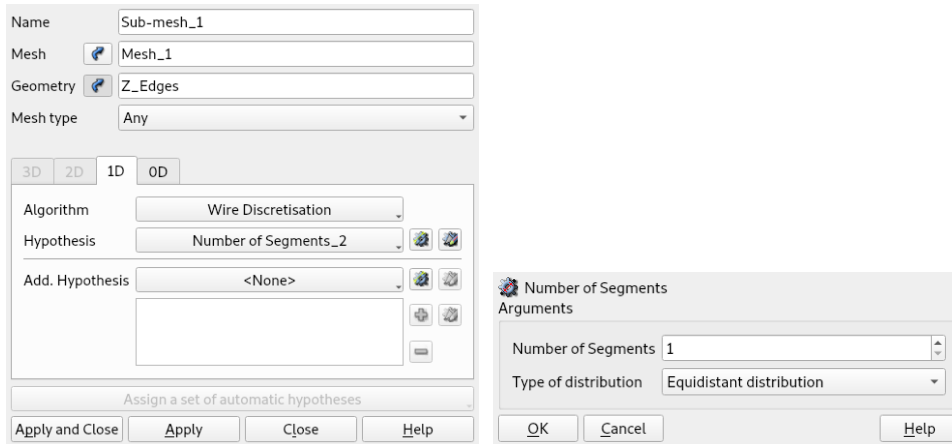


Figure III.11: Creating Z sub-meshes.

In the name field, enter **Sub-mesh_1**. The **Cavity_mesh** should already be selected in the Mesh field. If not, select it by clicking on **Cavity_mesh** in the Object Browser. Next, pick **Z_edges** for the **Geometry** field which stores the Geometry Objects the sub-mesh will apply to. Selecting an edge group for the **Geometry** automatically disables the 3D and 2D tabs in the **Algorithm** menu. Select **Wire discretisation** in the drop-down **Algorithm** menu and press on the gear button next to **Hypothesis** to specify the discretisation in its own pop-up menu. The **Number of Segment** object is renamed **X_discretisation** for future reference. Choose 50 segments with an **Equidistant distribution** and press **OK**. Returning to the **Create sub-mesh** menu, press **Apply** to instantiate the **Z_mesh** sub-mesh. The sub-mesh objects for the other two directions are defined similarly.

The mesh characteristics of the **Cavity** are now fully specified, as shown in Figure III.12 below where all the characteristics of **Mesh_1** and its sub-mesh have been listed.

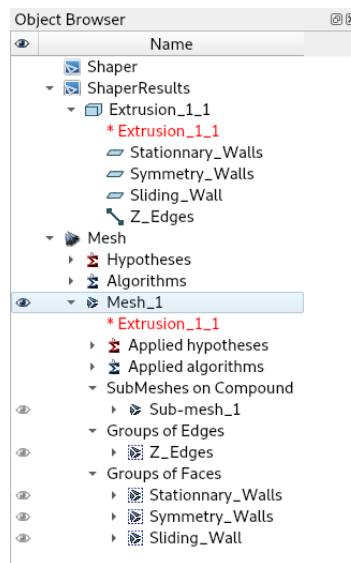



Figure III.12: Complete specification of **Mesh_1** and sub-meshes in the three directions.

To mesh the computational domain, right-click on **Cavity_mesh** in the Object Browser and select **Compute**, as shown in Figure III.13 below. Again, with **Cavity_mesh** selected, **Compute** can also be accessed via the main menu bar **Mesh** > **Compute** or via the short-cut icon .

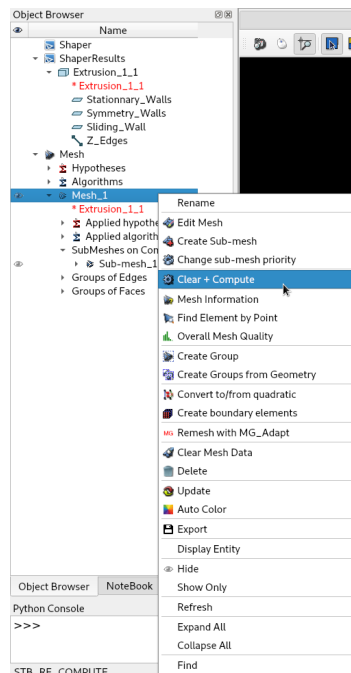


Figure III.13: Compute Mesh

The mesh is created and a pop-up window appears automatically summarising the mesh characteristics (Figure III.14).

Compute mesh				
<input checked="" type="radio"/>				
Name				
Mesh_1				
Mesh Infos				
	Total	Linear	Quadratic	Bi-Quadratic
Nodes :	5202			
OD Elements :	0			
Balls :	0			
Edges :	404	404	0	
Faces :	5200	5200	0	0
Triangles :	0	0	0	0
Quadrangles :	5200	5200	0	0
Polygons :	0	0	0	
Volumes :	2500	2500	0	0
Tetrahedrons :	0	0	0	
Hexahedrons :	2500	2500	0	0
Pyramids :	0	0	0	
Prisms :	0	0	0	0
Hexagonal prisms :	0			
Polyhedrons :	0			
<input type="button" value="Close"/> <input type="button" value="Help"/>				

Figure III.14: Resulting mesh.

Unlike Geometry module, Shaper module automatically creates boundary names under Mesh module. Before saving and exporting mesh file you could change **Part.1** name to **Cavity_mesh** by clicking over the part file with right mouse button and select Rename. Save the SALOME file and export

the mesh file in `.med` format by selecting from the main menu: **File** > **Export** > **MED file**, as shown in Figure III.15 below. The file should be placed in the `MESH` directory of the DrivenCavity study, where code_saturne will expect the file to be situated by default.

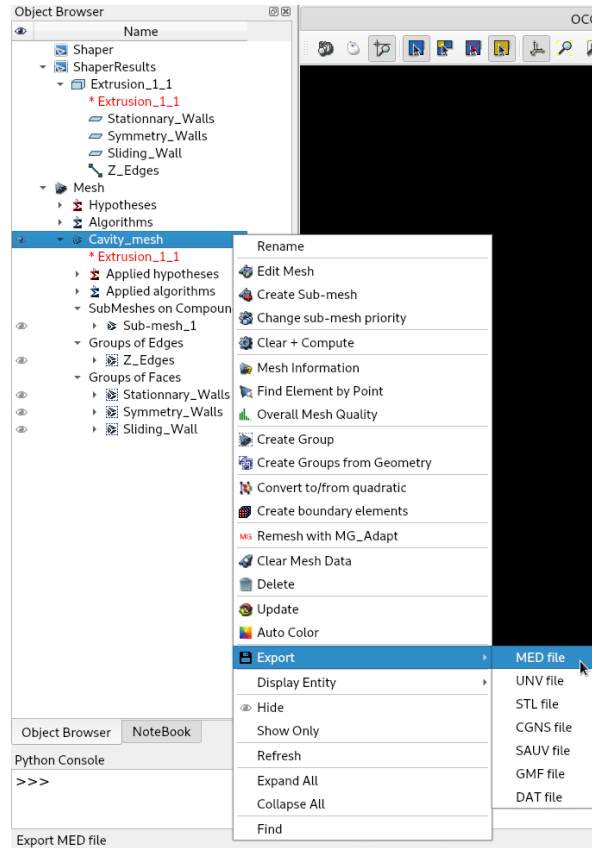


Figure III.15: Exporting the mesh file in `.med` format.

For the file name, choose **Cavity_mesh**; the `.med` extension is automatically added. You are now ready to set up the CFD simulation with the CFDStudy module.

3 Simulating within SALOME

3.1 Setting up the CFD Simulation

To set-up the CFD Simulation, select the CFDStudy module by clicking on the CFDStudy button or by selecting CFDStudy in the modules drop-down menu as shown in Figure III.16.

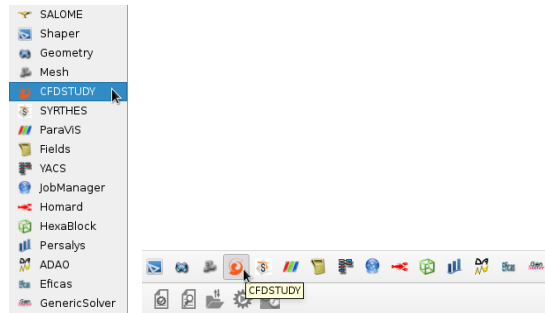


Figure III.16: Selecting the CFDStudy module.

Then, right click on **Reynolds1000** in the **Object Browser** and launch the code_saturne GUI inside the CFDStudy modules by clicking on **Launch GUI** as shown in Figure III.17 below.

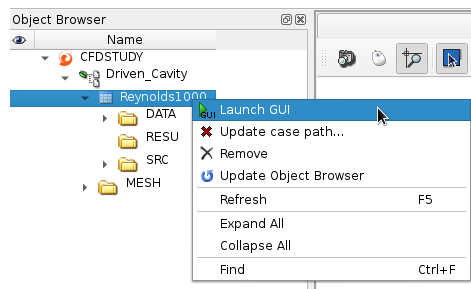


Figure III.17: Launching the code_saturne GUI inside the CFDStudy module.

Once the code_saturne GUI is open, it is advisable to start by saving your CFD set-up file. In the CFDStudy tool bar, click on the **Save CFD Data File** button (Figure III.18).



Figure III.18: Button bar of CFDStudy module.

By default, the file will be saved in the **DATA** directory and named **setup.xml**.

4 Simulating within code_saturne

Open code_saturne GUI as explained in Setting Up chapter of this document and check up your window. The latest should be similar to the figure [III.19](#)

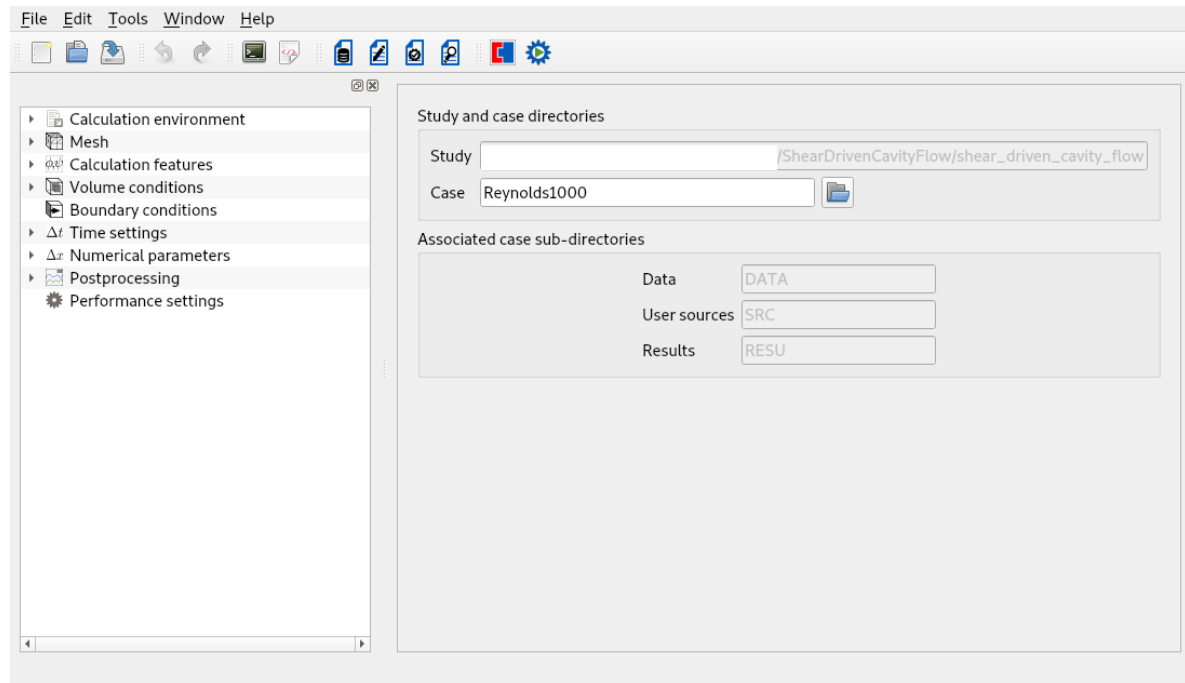



Figure III.19: Saving the code_saturne case.

You can now proceed with setting up the case, in the top down order of the folders in the left hand column of code_saturne.

Go to the [Mesh](#) Tab in order to specify the mesh file which will be used for these calculations.

4.1 Mesh Tab

Click on the  sign button below the table and a popup menu will show the content of the local mesh directory (here `../MESH`) from which the mesh file can be selected. Select the `Cavity_mesh.med` file previously exported from SALOME at the end of the meshing process, and press **Open**.

The file name will then be added to the list of meshes (Figure III.21).

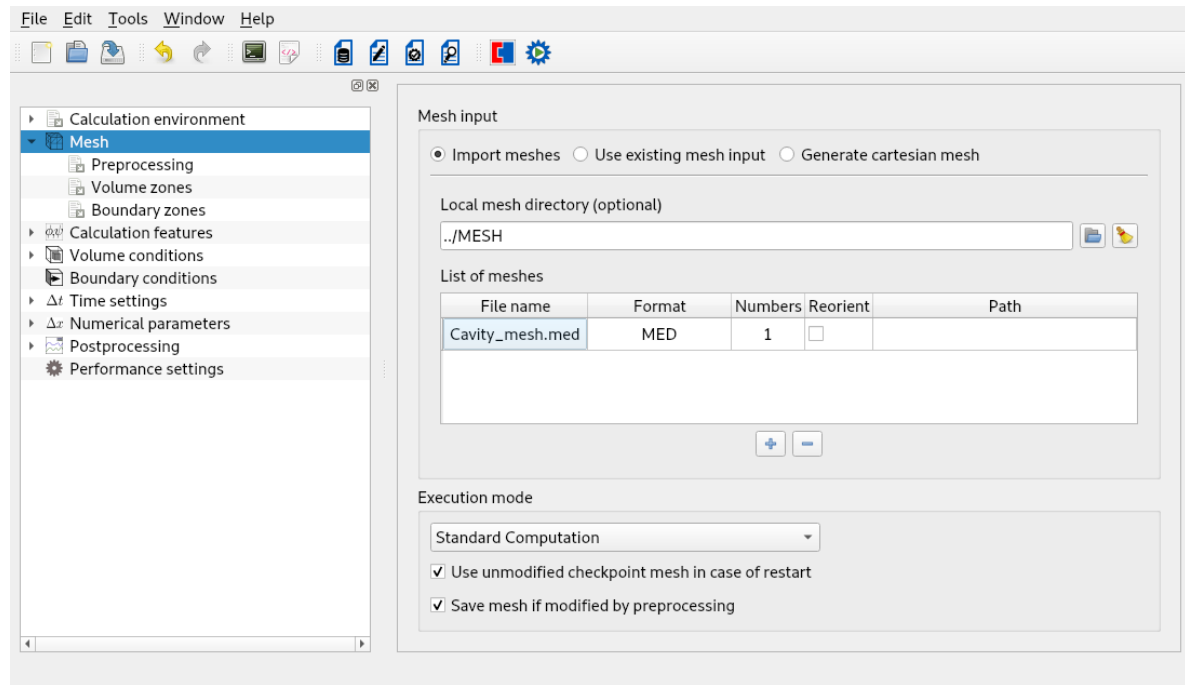


Figure III.20: Selecting the mesh file for the calculations.

Boundary zones Add three boundary zones by clicking on **Add**. Fill all fields (referring to III.3) as follows :

Zone	Selection criteria	Nature
1	Sliding_Wall	Wall
2	Stationnary_Walls	Wall
3	Symmetry_Walls	Symmetry

Table III.3: Boundary condition table

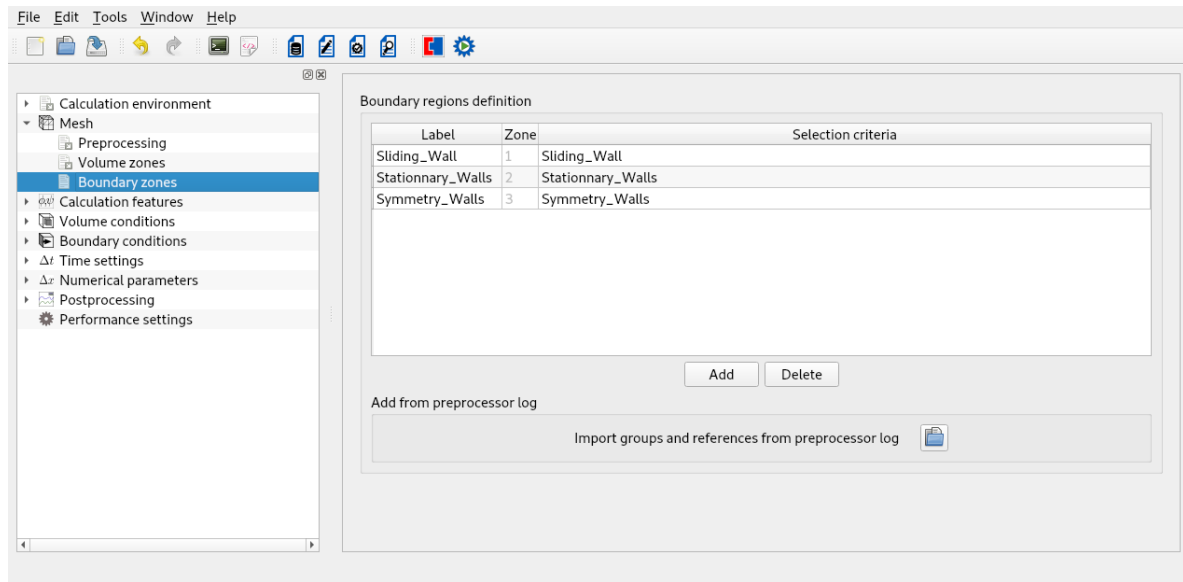


Figure III.21: Boundary Zones creation

No further input is necessary as the faces do not require reorientation, joining, or sub-dividing, and there are no periodic boundaries to be concerned with.

Alternativ procedure : There is another way to define boundary zones. The second method consist in :

1. **Computing a preprocessing mesh in order to generate a `preprocessor.log` file**
Select Mesh quality criteria only in the **Execution mode** zone

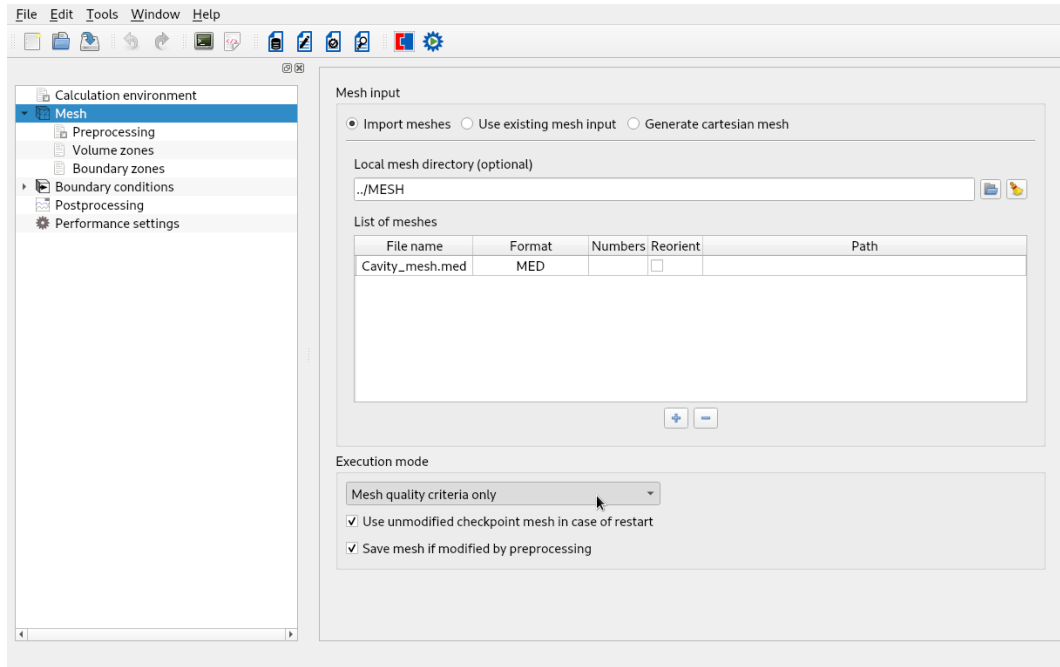



Figure III.22: Execution mode : Mesh Quality Criteria Only

To run the preprocessing mesh click on the  button

2. **Adding the `preprocessor.log` file**
In the **Boundary zones** tab, press **Import groups and references from Preprocessor log**. The **Select Preprocessor log** pop-up frame will then appear, which allows you to select the `preprocessor.log` file to use to load the boundary surfaces of the computational domain. You will then be able to apply specific boundary types to each of the surfaces or groups of surfaces. This file is in a directory called `quality_20190211-1630` for instance. In the pop-up frame, select the file `preprocessor.log` as shown in Figure III.23.

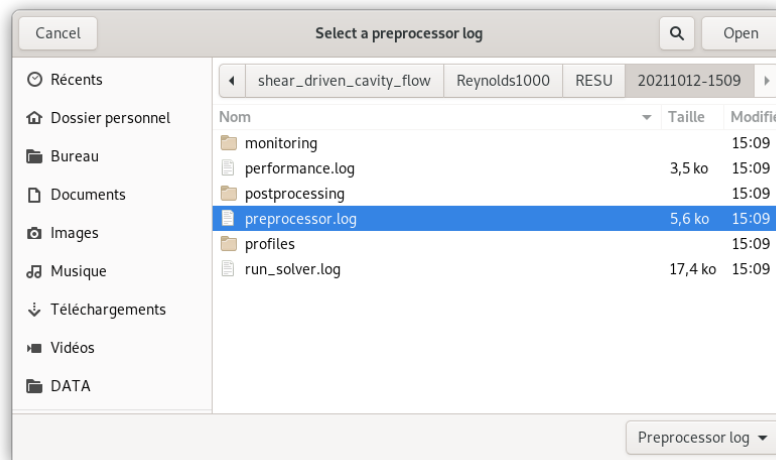


Figure III.23: Importing boundaries from the `preprocessor.log` file.

Don't forget to go back to **Standard Computation** in the **Mesh** tab.

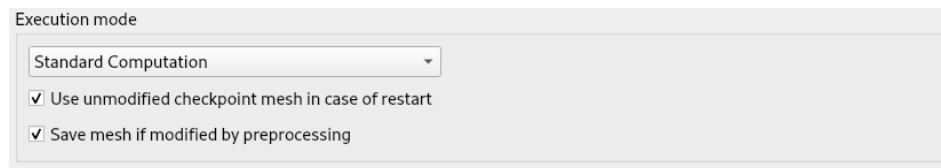


Figure III.24: Execution mode : Standard Computation

This alternative method could be useful only if all boundary zones are already well defined in the mesh file. If you have carefully followed mesh generation step in this document you would find exactly the boundary zone configuration as [III.21](#)

Next, move to **Calculation features** to specify physical fluid properties required for calculation.

4.2 Calculation features

Leave all the default values unchanged, all choices are disabled (Figure III.25), i.e. the incompressible Navier-Stokes model will be solved.

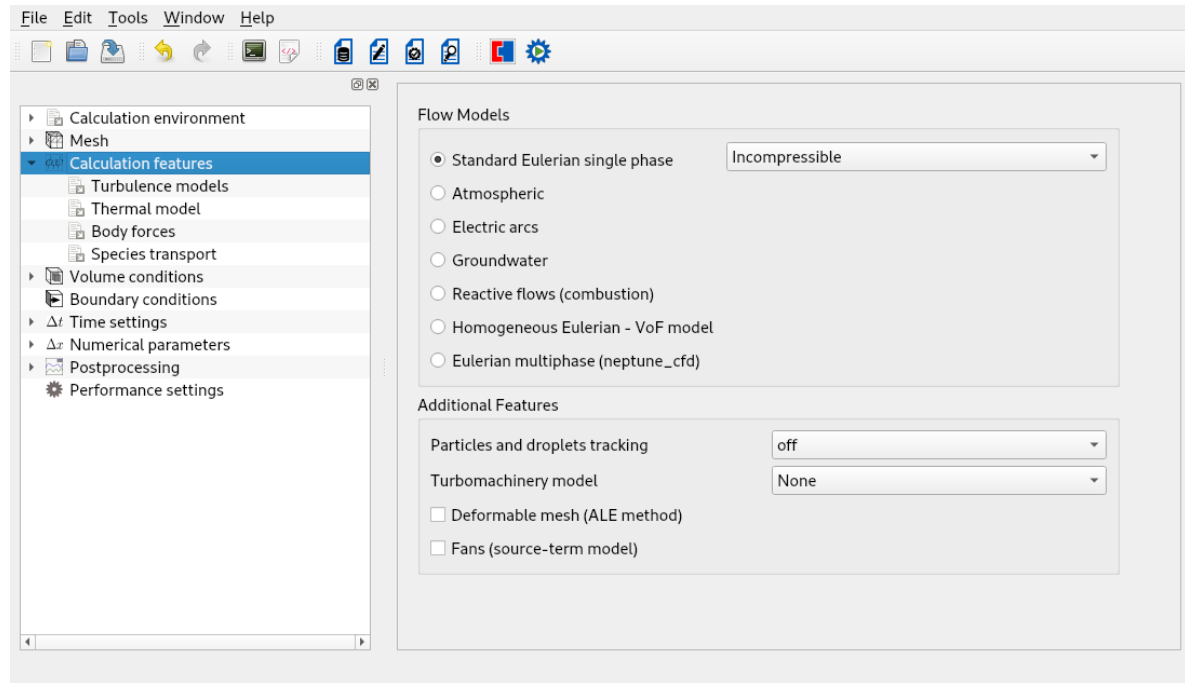


Figure III.25: Selecting the flow physics.

By default **Deformable mesh (ALE method)** and **Fans (source-term model)** are not selected. Continue setting up the **Calculation features**.

Turbulence models In **Turbulence models** we need select **No model (i.e. laminar flow)**, which is the correct flow regime for the flow Reynolds number that we have chosen in paragraph 1.2 (Figure III.26).

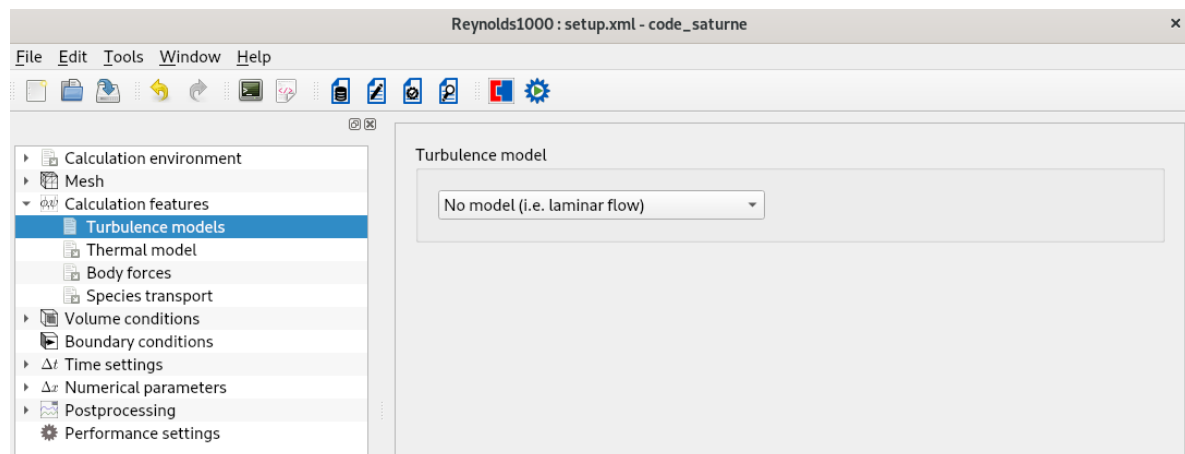


Figure III.26: Selecting a laminar flow (no turbulence model).

Thermal model is inactive by default. As our case is isothermal, it does not need to be visited and changed.

Save the file and, as there are no additional scalars, skip the **Species transport** and **Body forces** (as gravity is not a parameter of this problem (constant density) and **Coriolis source terms** are not taken into account in this tutorial.) categories and move to the **Physical Properties** folder where the thermal and physical characteristics of the fluid of interest for the calculations will be specified.

4.3 Volume conditions

Before stepping forward make sure these both options : **Initialization** and **Physical properties** are ticked.

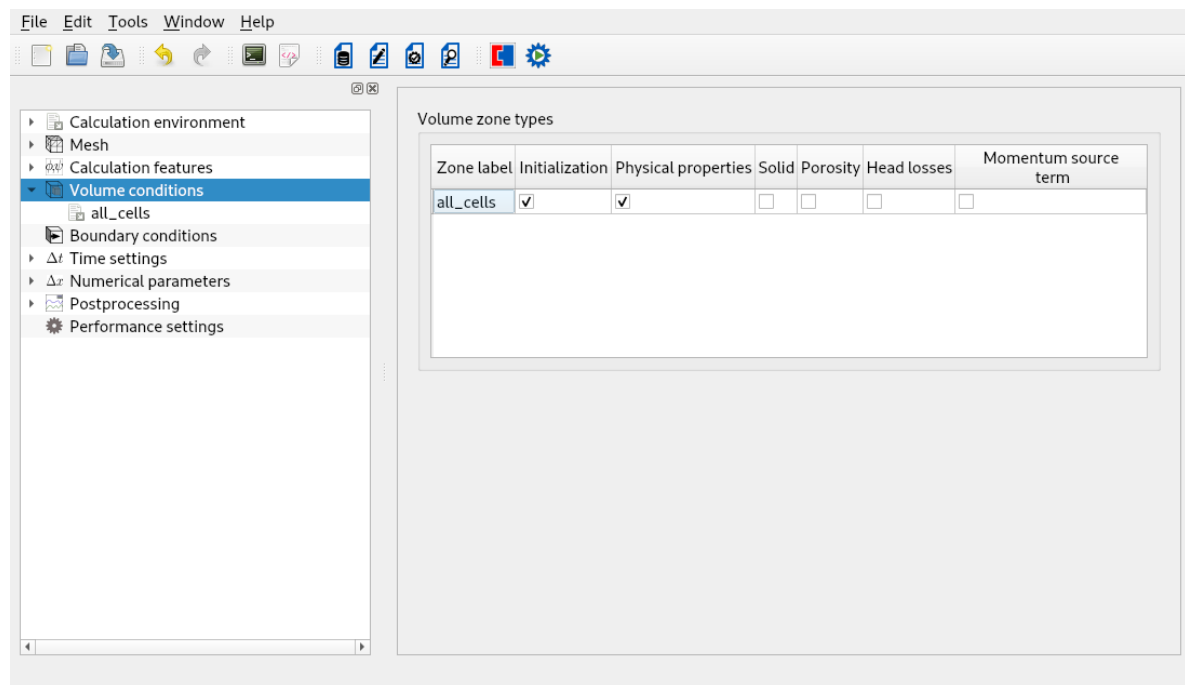


Figure III.27: Volume conditions

Physical properties First check on **Reference total pressure** value. This should be 101325.0 *Pa* by default. The other default values for velocity and length can also be left unchanged. However, some fluid Properties must be modified by clicking on **Physical properties** tab and, as per Figure III.28 below, altering the values of **Density** and **Viscosity** to the chosen values which are listed in Table III.1 above.

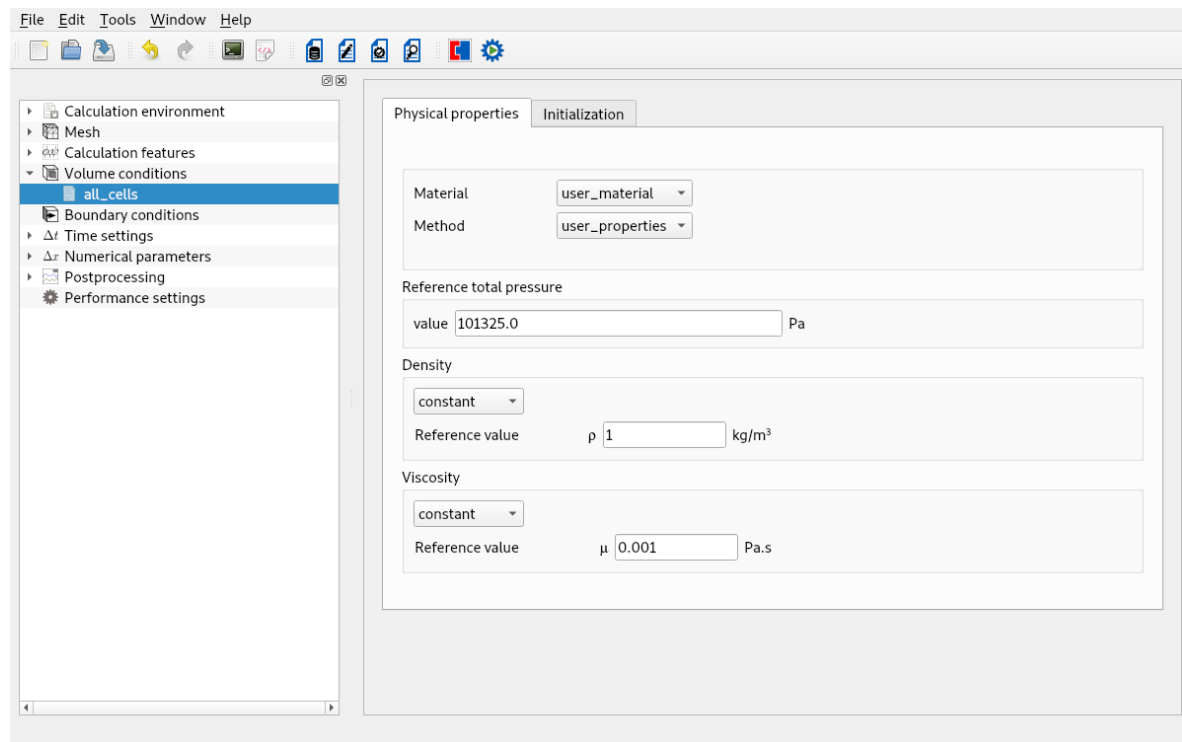



Figure III.28: Specifying the Physical properties.

Initialization To specify the initialization parameters click on **Initialization** sub-folder. In this sub-folder, press on the icon  next to **Velocity** to bring up the **Mathematical Expression Editor** and change the initial first component of the velocity to 0.1 *m/s* as shown in Figure III.29 below.

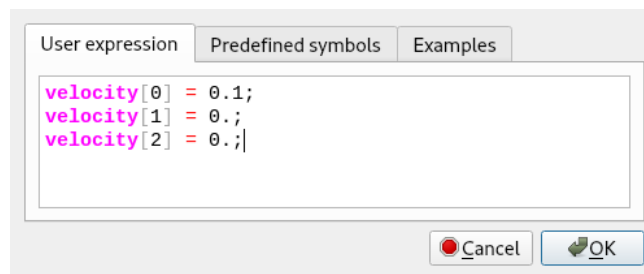


Figure III.29: Specifying velocity initial values.

4.4 Boundary conditions Tab

To define boundary conditions, go to [Boundary zones Tab](#). You must define the nature of all boundary zones previously created.

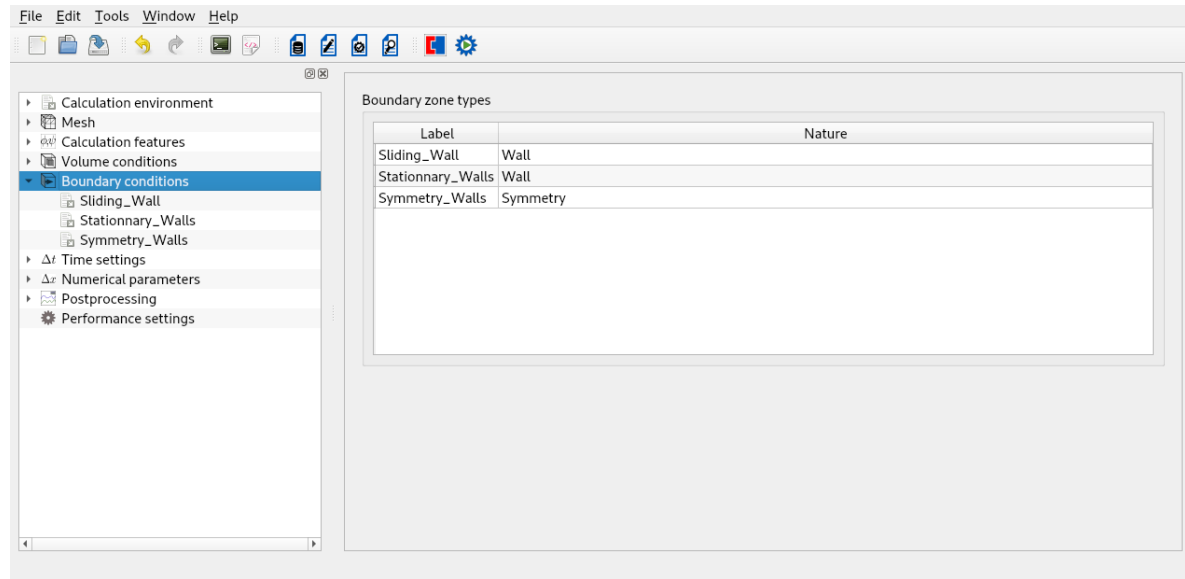


Figure III.30: Boundary definition

Having defined their type, the exact characteristics of the boundaries must be further specified. Click on the [Boundary conditions](#) sub_tabs which presents the list of boundaries which can be further specified (Figure III.32). By default, the wall surface is **smooth** and this parameter does not need to be changed.

Stationnary wall Leave all default option as follows



Figure III.31: Specifying stationary wall.

Sliding wall Click on the [Sliding-wall](#) boundary and activate the [Sliding wall](#) selection. Fields then appear for the **U**, **V**, and **W** velocity components of the wall. By default, these velocities are null. Click in the **U** field and enter 1.0, as shown in Figure III.32.

Sliding_Wall [Wall]

Smooth or rough wall

☒ Smooth wall ☐ Rough wall

☒ Sliding wall

U m/s V m/s W m/s

Figure III.32: Specifying stationnary wall.

Symmetry planes The **symmetry boundaries** are fully defined and do not need further specification. Therefore, they do not appear in the list.

The mesh and physics of the problem have now been set up. Now, parameters related to the calculation can be specified.

4.5 Time settings Tab

To set the duration of the run and the time step, move to the **Time settings** folder. Change **Constant** to **Time varying (adaptive)** at the **Time step option**. Then, change the **Stopping criterion** to **Number of time steps** and set it up to 400. Finally, increase the **Maximal CFL number** to 8.0, leaving the other parameters unchanged (Figure III.33). By default, the calculation-restart is disabled in **Start/Restart** and so this sub-tab does not need to be visited.

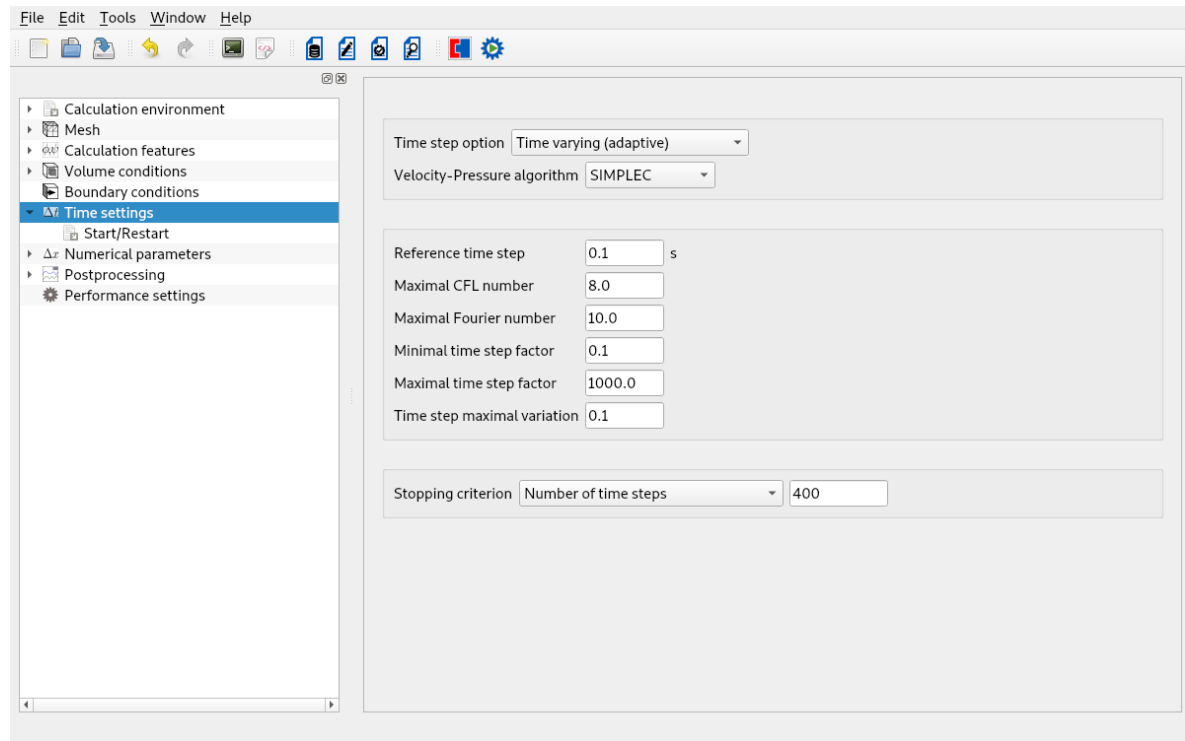


Figure III.33: Selecting the number of iteration and CFL number.

4.6 Numerical parameters Tab

Equation parameters In **Numerical Parameters**, leave the settings unchanged in the **Global parameters** and move to the **Equation parameters** sub-folder. In the **Scheme** tab, apply the **Centered** scheme and disable the **Slope test** for the velocity (Figure III.34). The former will provide second-order accuracy in space and the latter is unnecessary for a smooth flow.

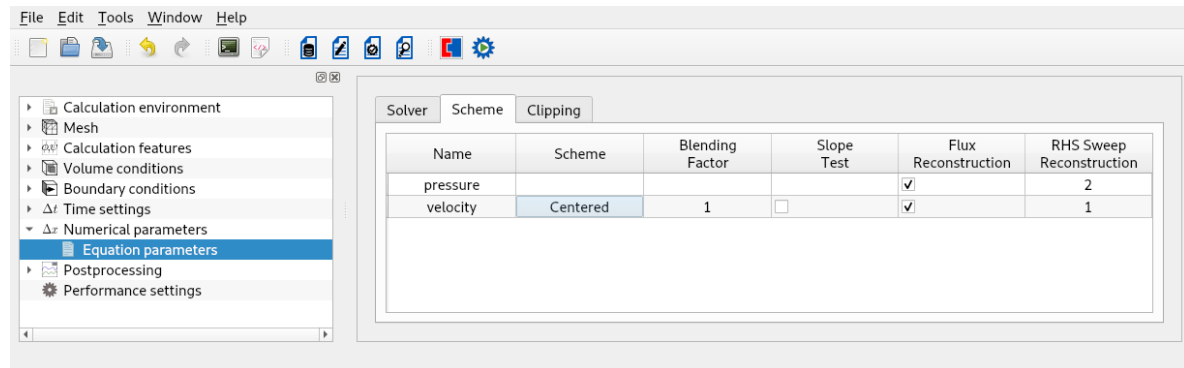


Figure III.34: Specifying the flux schemes.

4.7 Postprocessing Tab

Move to the **Postprocessing** section. **Time averages** are not of interest for these simulations and the sub-folder does not need to be visited. However, we want to keep track of the solution at different monitoring points to see how it evolves during the calculations. Aside from the solution residuals and the minimum and maximum values of the flow variables which code_saturne outputs during the calculations, tracking the solution at significant monitoring points is a very important mean of gaining confidence in the convergence of the calculations and judging whether calculations have been run for a sufficiently large number of iterations. This is explained further in paragraph 4.8 below.

Click on the **Postprocessing** folder panel. The first three tabs, **Output control**, **Writer**, and **Mesh** are set by default to the correct values for this case and do not need to be changed. The **Log frequency** in the **Output control** tab is set to print the calculations diagnostics such as the residuals at each time step.

Writer In the **Writer** tab, the format of the **results** file which will be used for post-processing is already set to **EnSight**, which is compatible with the SALOME module **ParaVis** which will be used to post-process the results after the run. The file will be located in the `postprocessing` sub-directory of `Reynolds1000/RESU/runDateAndTime`, where `runDateAndTime` corresponds to the time at which the run was started. Clicking on the **results** row brings up the additional information about the **Frequency**, **Time-dependency** and **Options**. As already set by default, the **results** file will only be written at the end of the run and on the **Fixed mesh** used for this case. The **Options** relate to the specific details of the file format. The **Mesh** tab is already set to output the calculations data in all the fluids cells and at all boundary faces to the **results** file.

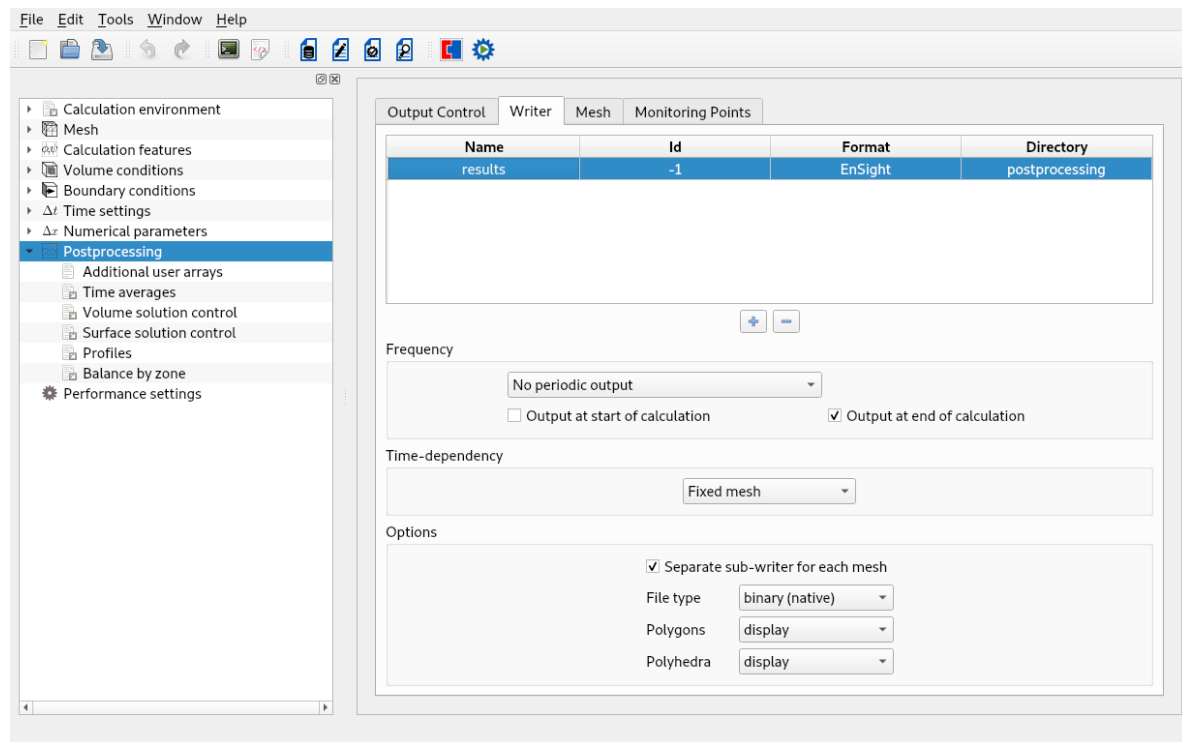



Figure III.35: Postprocessing Tab - Writer options

Monitoring Points In the **Monitoring Points** tab use the  button in order to add four monitoring points located at (0.25, 0.5, 0.0), (0.5, 0.25, 0.0), (0.5, 0.75, 0.0) and (0.75, 0.5, 0.0) (Figure III.36).

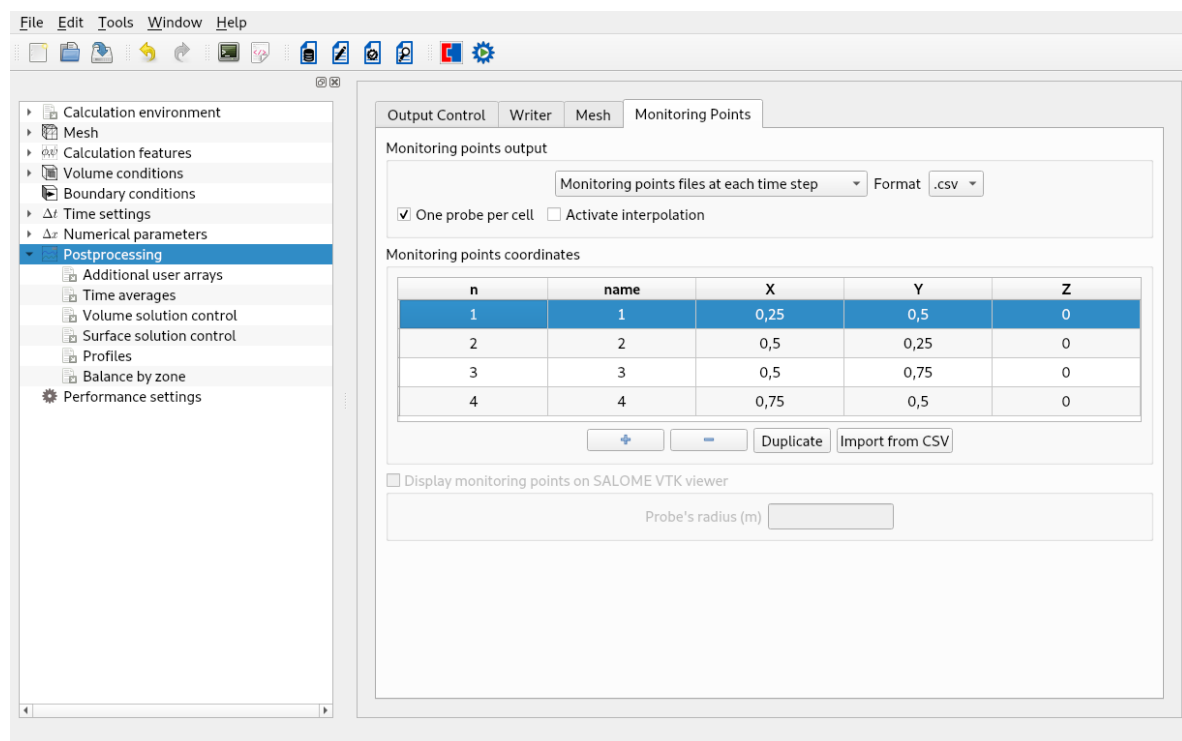


Figure III.36: Defining the monitoring points.

Surface solution control Click on the **Surface solution control** sub-folder and disable **Post-processing** for **Yplus** and **Stress** as they are not relevant to these simulations (Figure III.37)

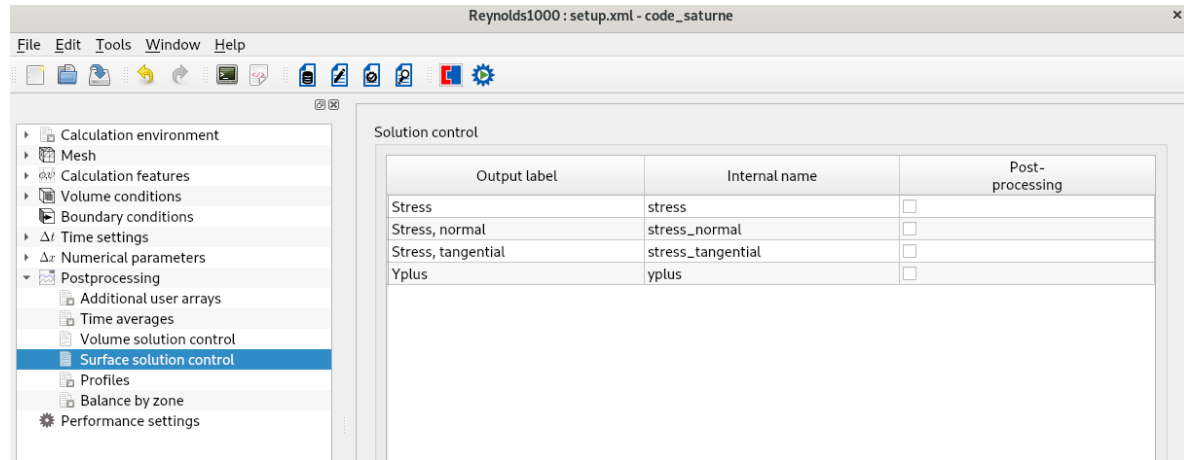


Figure III.37: Selection of output variables on the surfaces of the domain.

Profiles Lastly, we want to output one-dimensional profiles of variables along straight lines at the end of the calculations. Click on **Profiles** and add two profiles which go through the centre of the Cavity by clicking on the **Add** button. The first one for the X velocity along the Y axis and the second one for the Y velocity along the X axis. In turn, specify all the fields listed below the table of profiles, starting with **Filename** and finishing with the variables which are to be stored on output.

For the X velocity profile, choose **XVel.YaxisCenterLine** for **Filename**, and **.csv** for **Format** so that the profiles may be read in the ParaVis post-processing module of SALOME. The **Output frequency** must be set to **at the end of the calculation**. To define the line, press on the **Mathematical expression editor** button adjacent to **Line Definition**. The line is defined by the following equation :

$$\begin{cases} x &= 0.5 \\ y &= s \\ z &= 0.0 \end{cases}$$

By definition, s varies between 0 and 1.0. For the **Number of points** enter 50 to account for the 50 cells across the domain's height. Finally, click on **Velocity[0]** and use the **→** button to add it in the list of variables, and press **Add** to store the profile in the list (Figure III.38).

Repeat the procedure for the Y -velocity profiles, this time entering **YVel.XaxisCenterLine** for **Filename**, and the following equation for the line definition :

$$\begin{cases} x &= s \\ y &= 0.5 \\ z &= 0.0 \end{cases}$$

Select the **Velocity[1]** variable instead of **Velocity[0]**. The **Reynolds1000** case CFD simulation is now ready to run.

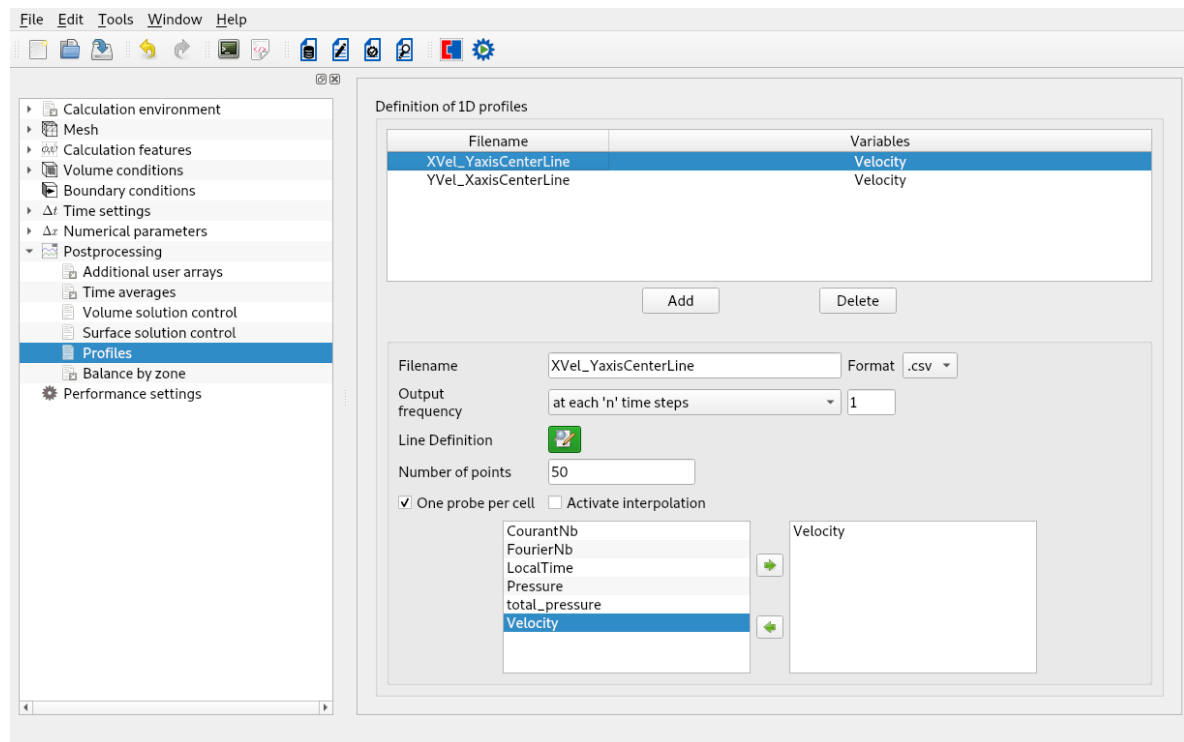


Figure III.38: Specifying the 1D output profiles.

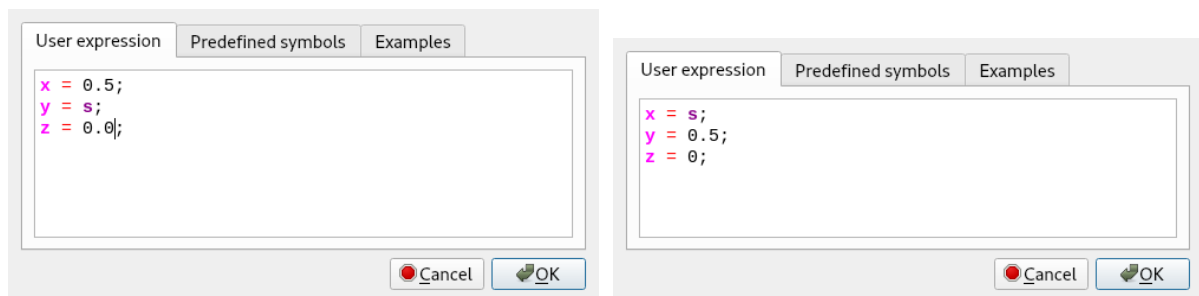



Figure III.39: Line Definition - XVel_YaxisCenterLine(left) and YVel_XaxisCenterLine(right)

To run the case click on the  button

A new window will open. Choose **1** processor for the **Number of processes**. Leave the **Result subdirectory name** and **Threads per process** to their default value.

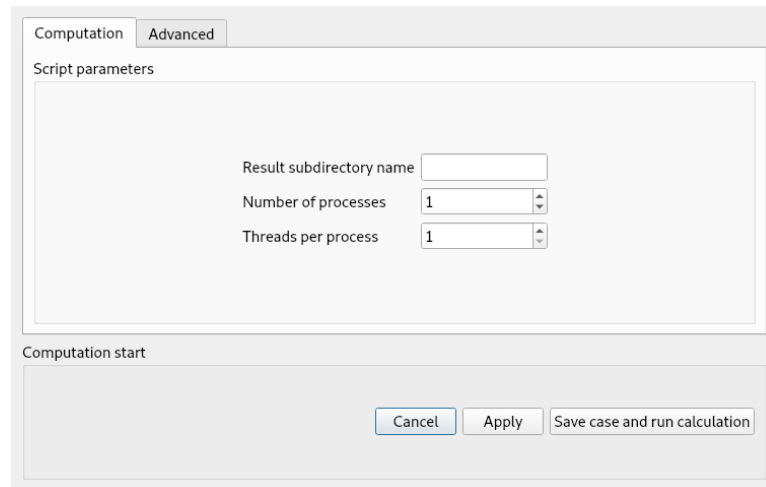


Figure III.40: Run

Press the **Save case and run calculation** button to run the computation.

4.8 Running and Analysing the Simulation

Upon firing the code_saturne run from the GUI, confirmation that code_saturne is running, “code_saturne is running”, appears in the window from which the GUI was started. This is followed by further messages indicating what stage the calculation is in, from “Preparing calculation data” to “Post-calculation operations”.

Wait for the calculations to complete and enter the `Reynolds1000/RESU` directory or open its contents via a browser to inspect its contents. Explanations of the meaning and purpose of the different output files and directories resulting from a run are available in the code_saturne Users Guide [3] and are not repeated here. Instead, we highlight individual items which relate to this specific run and how the output information should always be used in order to analyse a calculation.

The `RESU` directory now contains a new directory named after the date and time at which the calculation was started, expressed on a 24 hours clock in the format “YearMonthDay-HourMinutes”.

In this latter directory, notice in particular:

- The profile files `XVel.YaxisCenterLine` and `YVel.XaxisCenterLine`, written in `.csv` format,
- The `listing` file,
- The `monitoring` and `postprocessing` directories.

With your text editor, open one of the profile files, to inspect its structure. The requested variables listed in column format as a function of the (x, y, z) coordinates of the points along the profile line defined in the GUI.

Open the `listing` file to check that the calculation has converged towards stable values. The minimum and maximum values of the solution variables and the solution residuals for these variables are listed in summary tables at each iteration. By comparing the initial and final values in the **Drift** column for each variable, and their evolution throughout the calculation, check that the residuals have decreased by at least two orders of magnitude.

** INFORMATION ON CONVERGENCE

Variable	Rhs norm	N_iter	Norm. residual	Drift	Time residual
c Velocity	0.24719E-03	8	0.14525E-01	0.10121E+00	0.24951E+02
c Velocity[X]				0.10037E+00	
c Velocity[Y]				0.84043E-03	
c Velocity[Z]				0.93180E-29	
c Pressure	0.19612E-03	22	0.55472E-08	0.10000E+01	0.90909E+01

Figure III.41: code_saturne Convergence history from the listing file, after 1 iteration.

** INFORMATION ON CONVERGENCE

Variable	Rhs norm	N_iter	Norm. residual	Drift	Time residual
c Velocity	0.28301E-03	5	0.92835E-08	0.97911E-15	0.17206E-06
c Velocity[X]				0.37050E-15	
c Velocity[Y]				0.60861E-15	
c Velocity[Z]				0.40713E-38	
c Pressure	0.35145E-10	0	0.67751E-07	0.67751E-07	0.80326E-15

Figure III.42: code_saturne Convergence history from the listing file, after 400 iterations.

Inspect one of the monitoring files in the `monitoring` directory. The value of each variable is recorded in separate files at all the monitoring points defined in the GUI and as a function of iteration.

Finally, verify that the `RESULTS_FLUID_DOMAIN.case` file containing all the mesh and output variables information for post-processing has been output in the `postprocessing` directory.

Having validated the calculation itself, you can now proceed to examining and post-processing the results by returning to the SALOME platform.

4.9 Post-processing the Results

In SALOME, select **ParaViS** from the drop-down module selector in the top menu bar. The name of the module will add itself to the Object Browser list and the ParaView-specific panels and menus will be activated, including a new **ParaView scene viewer** window.

Before loading the run data in ParaView, modify the default colour schemes. To visualise scenes on a white background, which is advantageous for printing, change the default settings for ParaView by clicking on `File > Preferences` in the top menu. For **ParaViS**, in the **ParaView Settings** tab, change the colours to black for the foreground and text, white for the background, and grey for the surfaces, as shown in Figure III.43 below. Press `Apply` to enforce the new settings and `OK` to validate your selection when you are satisfied with the changes.

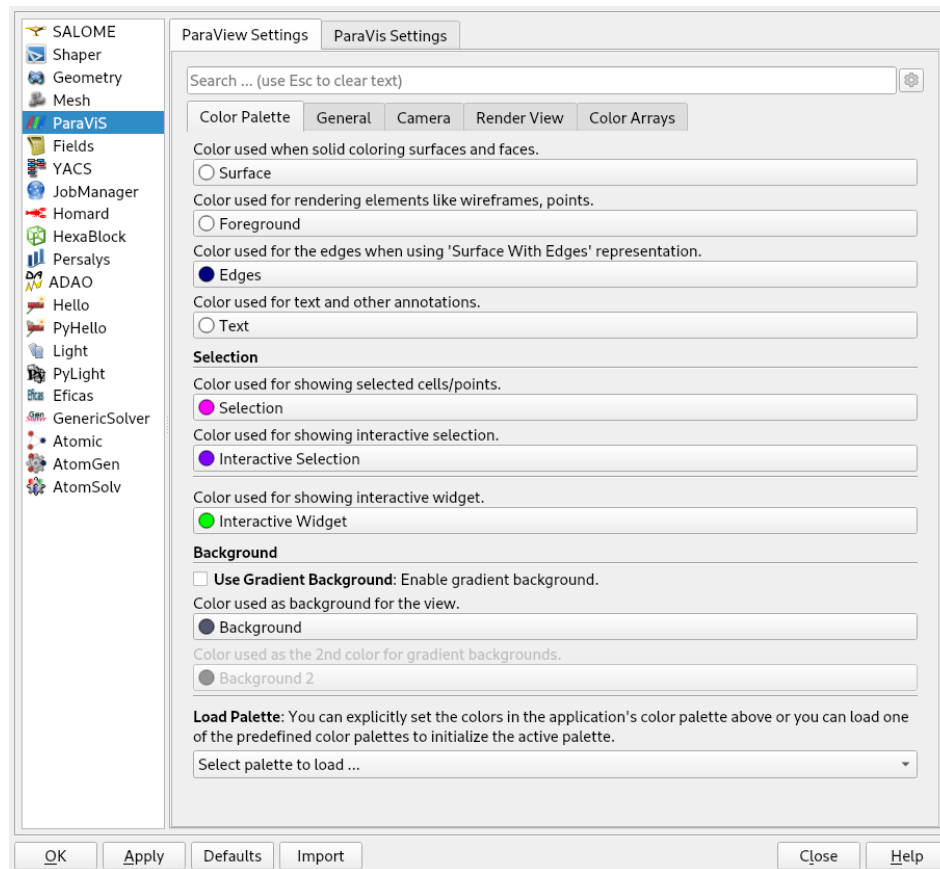




Figure III.43: Setting the colour preferences for ParaView.

The data to post-process can now be imported in ParaView.

First, you are going to load the monitoring point data to validate that a stable, steady-state solution has been obtained. From the top menu bar, select **File** > **Open ParaView File**. In the **Open File** pop panel, navigate to the **monitoring** sub-directory and select three files. The multiple selection is performed by holding the **Ctrl** key down as you select the files. Select **probes.Pressure.csv**, **probes.Velocity[X].csv**, and **probes.Velocity[Y].csv**. Close the panel by clicking **OK**. The three sets of data are now displayed under their file name in the **Pipeline Browser**. For each file, press **Apply** to load the data. By default, the data is visualised in tabular form in the ParaView scene viewer. Close the View by clicking the cross button  at the top, right hand corner of the view. Then, click on the  button to replace the data view by a **Create View** menu (Figure III.44).

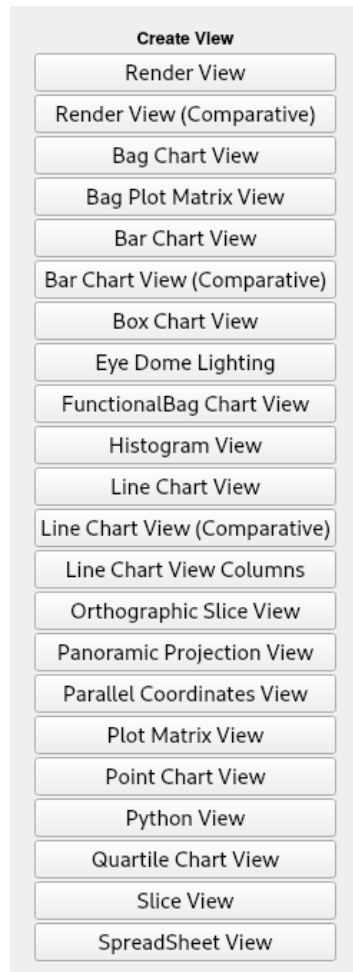



Figure III.44: ParaView **Create View** menu.

Click on the **Line Chart View** button and prepare the line plots, starting with the pressure data. Make the data visible for that file by clicking on the eye symbol  next to the file name in the **Pipeline Browser**. Go to the **Display** tab and set **Attribute Type** to **Row Data**. In the **Series Parameters** category, unselect the **time** variable. The variables **1**, **2**, **3**, and **4**, representing the pressure at each iteration at the four monitoring points you specified should be selected and the graphs of their evolution as a function of the number of iterations (time steps) should now be displayed in the view window. For clarity, change the legend for each variable. In the **Series Parameters** category, left-click on the row for variable **1** to select it. Double left-click on the name of that variable, in the **Legend Name** column to edit it. Change the name of each variable to **Pressure (1)**, **Pressure (2)**, **Pressure (3)** and **Pressure (4)** (Figure III.45 and III.46).

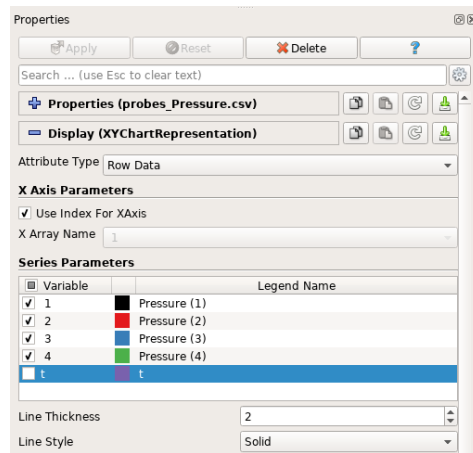


Figure III.45: Specifying the line plot's legend.

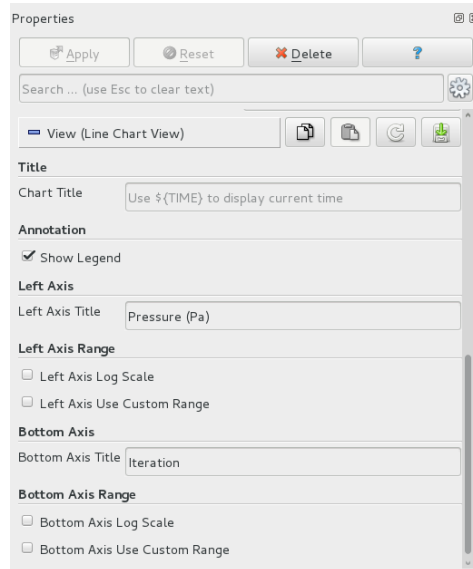


Figure III.46: Specifying the line plot's axes.

In the View window's tool bar Change the **Bottom Axis** title to **Iteration**, and the **Left Axis** title to **Pressure (Pa)** (Figure III.47). The graph shows that the pressure at the four monitoring points becomes constant after about 100 iterations (Figure III.47).

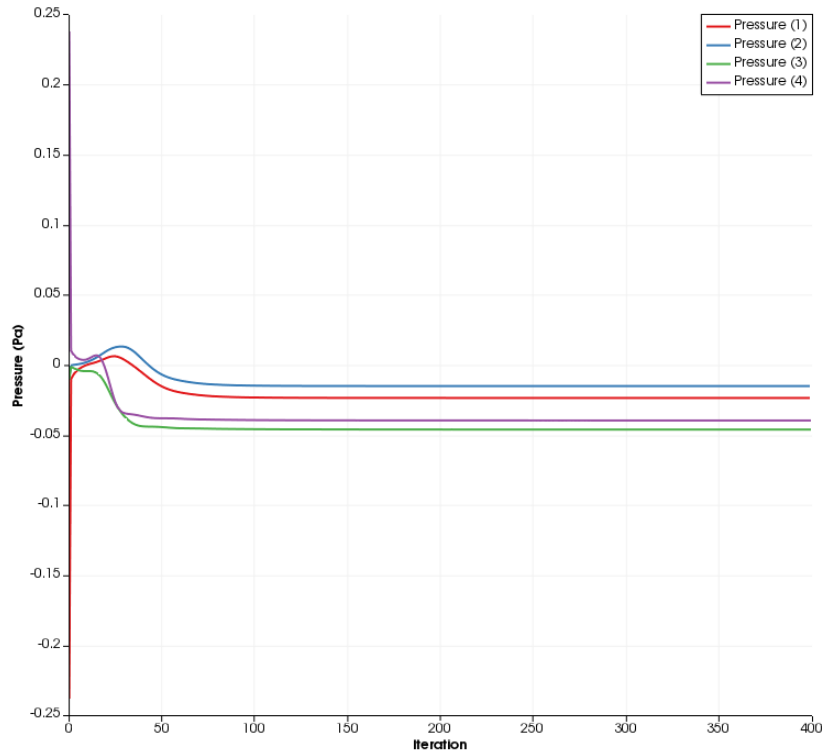
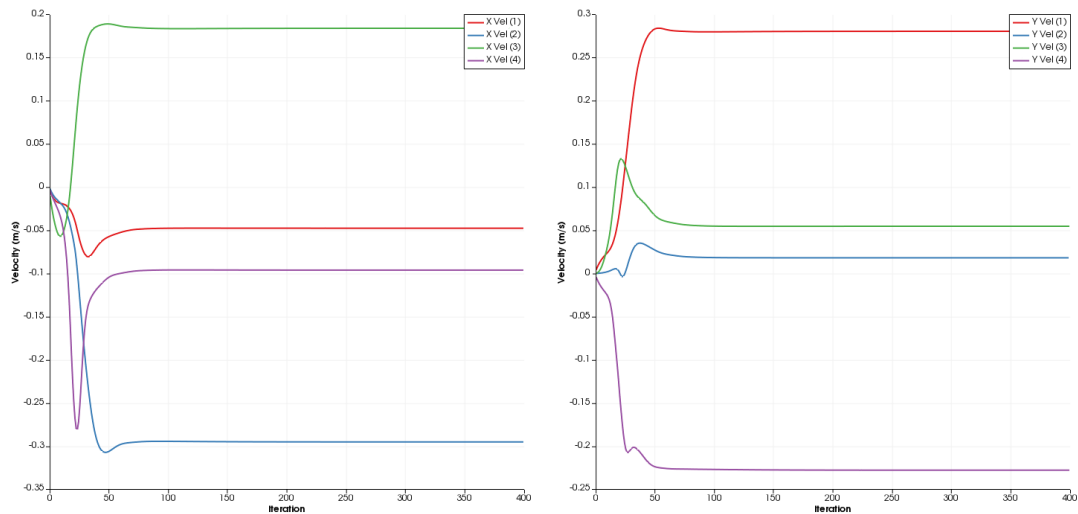


Figure III.47: Pressure at the four monitoring points as a function of iteration.

Repeat the same operation for the remaining velocity files. For both files, change the left axis title to **Velocity (m/s)**. For the X velocity, change the variable names to **$X\ Vel(i)$** , where $i = 1, 2, 3$, and 4. Keep the default colours for each line so that they are consistent for each monitoring point. For the Y velocity, change the variable names to **$Y\ Vel(i)$** , where $i = 1, 2, 3$, and 4. The graphs also confirm that the velocity components at the four monitoring points settle to a stable, constant value after about 100 iterations, indicating that the calculations are converged (Figure III.48).

Figure III.48: Velocity components (X (left), Y (right)) at the four monitoring points as a function of iteration.

You may now post-process the results from the calculations. From the top menu by selecting **File** **Open ParaView File**, or by right-clicking on the **builtin** object in the Pipeline Browser panel and selecting **Open**, access the pop-up **Open File** panel and choose the **RESULTS_FLUID_DOMAIN.case** file from your run. The **RESULTS_FLUID_DOMAIN.case** object will be added to the **Pipeline Browser** and its contents displayed in the **Object Inspector** panel underneath. Press **Apply** to load the data in ParaViS.

Sometimes you need to extract the computed data in terms of fluid domain and boundary data, to do so, go to the top menu bar and click on **Filters** **Alphabetical** **Extract Block**. The new object **ExtractBlock1** will appear in the **Pipeline Browser**. With the object highlighted, move to the **Block Indices** panel of the **Properties** tab. In the data tree, under **Root**, select **Fluid domain** to visualise the data calculated at the cell centres inside the cavity walls. Here, we already have two separated cases (Fluid domain and Boundary) so we will only have to select **RESULTS_FLUID_DOMAIN.case** and press **Apply**, as shown in Figure III.49.

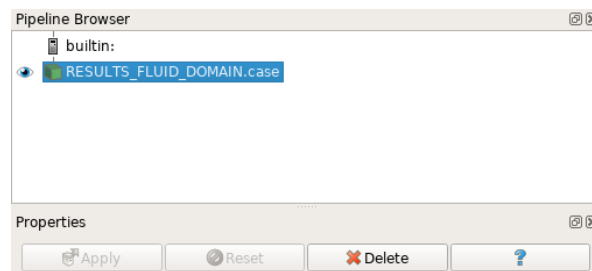


Figure III.49: Extract the **Fluid domain** block in ParaViS.

Left click on the **Display** tab of the **Object Inspector**. In the category **Coloring**, two drop-down menus allow you to choose the variable to visualise. Choose **Velocity** in the first one and **Magnitude** in the second one, as shown in Figure III.50.

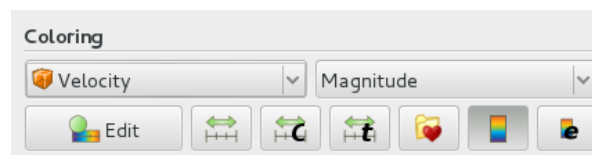


Figure III.50: Velocity magnitude variable chosen to color the fluid domain.

Contour plots of the velocity magnitude are then displayed in the **ParaView scene viewer**. By default, the colour scale is set to the **Cool to Warm** (RGB) colour scheme which is inadequate.

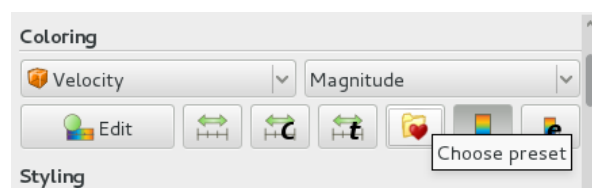


Figure III.51: Color map editor.

To modify the visualisation colour scheme, click on the **Choose Preset** button (see Figure III.51) button and select **Blue to Red Rainbow** (HSV) in the list of **Preset Color Scales**. If it doesn't appear in the list you can Press **Apply** and then **Close**.

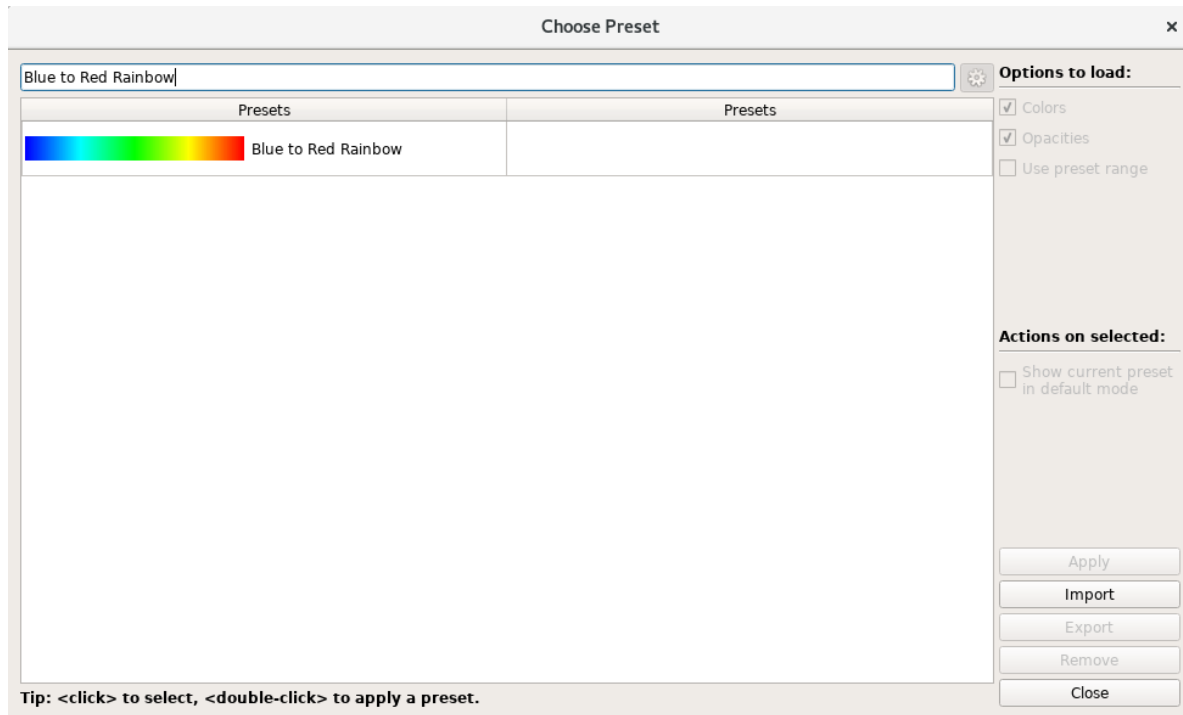



Figure III.52: Selecting the visualisation colour defaults.

Press the  **Save current display settings values as default** button to save the changes. The contour plot of velocity magnitude is now updated for the new colour scale (Figure III.53).

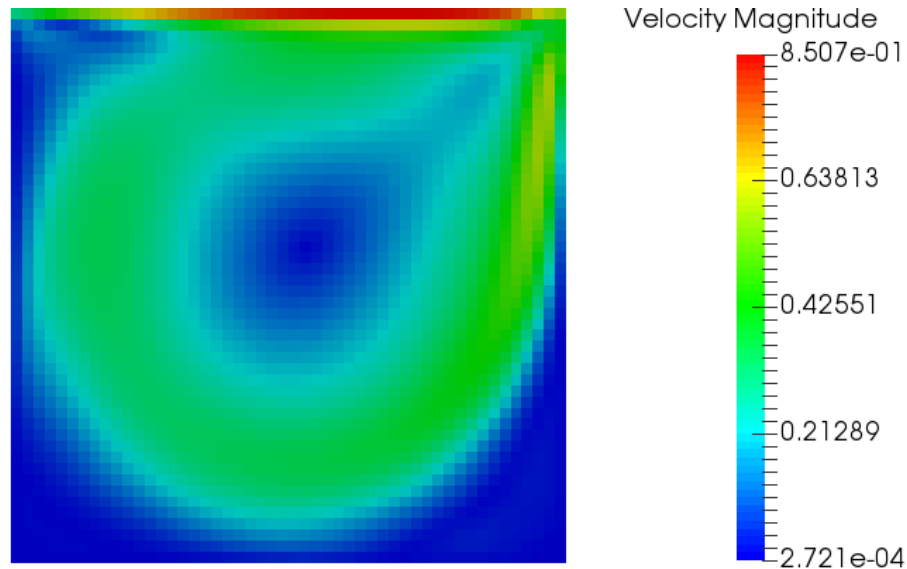


Figure III.53: Contour plot of velocity magnitude.

The contour plot indicates that there is a zone of higher velocity flow defined by the green and red zones surrounded by lower and no-velocity regions in blue. Consistent with the chosen boundary conditions, the maximum velocity is equal to 1.0 m/s at the top, sliding wall and decreases to zero at the other, non-slip walls.

With the HSV colour scale, the contour plot is now clear, with the different levels clearly differentiable,

but the image looks tessellated. As code_saturne outputs data at cell centres in the **results** file, in ParaView each mesh cell is painted with a pixel of colour corresponding to the exact value of the variable in the cell. Whilst this cell-data visualisation mode is correct to examine exact values at cell centres, it can yield ragged images unrepresentative of the solution's higher-order spatial accuracy and cannot be used in ParaView to generate vectors and streamline plots. Instead, to produce smoother images, and vector and streamline plots, the cell-data can be interpolated to cell vertices (corners) using the ParaView **CellDatatoPointData** filter.

Having clicked on **RESULTS_FLUID_DOMAIN.case** in the Pipeline Browser to select it, in the top menu bar click on **Filters** > **Alphabetical** > **CellDatatoPointData**. The new object, which now stores the **RESULTS_FLUID_DOMAIN.case** data interpolated to cell vertices, is added in the Pipeline Browser (Figure III.54).

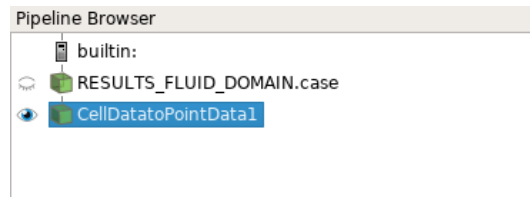


Figure III.54: **CellDatatoPointData** filter added to the Pipeline Browser.

With **CellDatatoPointData** selected in the Pipeline Browser, click **Apply** in the **Properties** tab of the **Object Inspector** to bring up the smoothed-out contour plot in the **ParaView scene viewer**.



Figure III.55: ParaView short-cuts.

Picking the different variables to map, either from the **Display** tab in the Object Inspector for the **CellDatatoPointData** object or directly from the drop-down list in the menu bar for contour plots at the top of the SALOME window (see Figure III.55), create contour plots for the **X** and **Y** velocity components, as shown in Figure III.56 below. The plots use a **Surface** mode of **Representation**, which can be selected either from the **Display** tab and **Representation** category, or directly from the drop-down list in the contour plot menu bar (see Figure III.55).

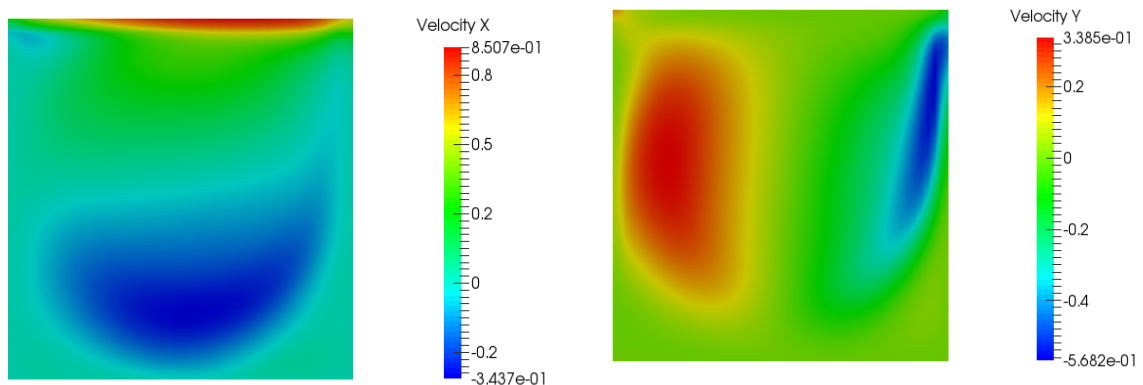


Figure III.56: Contour plots of the **X** (left) and **Y** (right) velocity components.

As expected, the maximum velocity in the **X** direction occurs at the top wall, where it nears 1.0 m/s

(Figure III.56 (left)). The locations of the blue (flow in the negative direction) and red (flow in the positive direction) areas in both plots (Figure III.56) indicate that the flow is entrained by the top wall in a clockwise circular motion inside the box. These plots are useful to verify overall velocity magnitudes and patterns but, to get a better visualisation of the flow, one can create 2D glyphs which shows velocity vectors and streamlines which will show fluid particles trajectories.

To create the 2D glyphs, select **CellDatatoPointData** in the Pipeline Browser and click on **Filters** **Common** **Glyph** in the top menu. The **Glyph1** object is then added under **CellDatatoPointData** in the Pipeline Browser. Keep the **CellDatatoPointData** object selected and visible (👁 icon in bold next to the object). In the Object Inspector, select the **Properties** tab. In the **Glyph Source** category, choose **2D Glyph** in the **Glyph Type** drop-down list. In the **Scale** category, choose **Velocity** in the **Scale array** drop-down list and **Scale by Magnitude** in the **Vector Scale Mode** drop-down list (see Figure III.57). Press **Apply**.

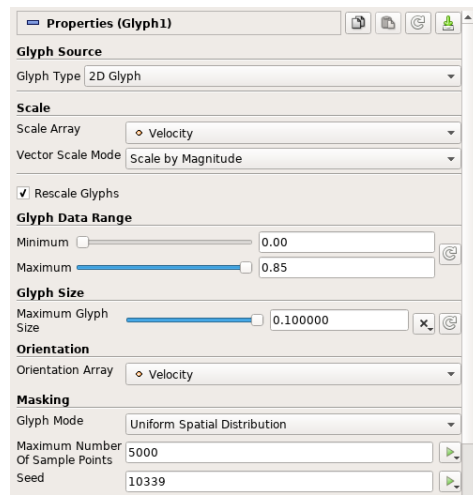


Figure III.57: Glyph type and Scale Mode.

In the Object Inspector, select the **Display** tab. In the **Coloring** category, choose **Solid Color** and set this color to black by clicking on the **Edit color map** button (see Figure III.58). Press **OK** to finish.

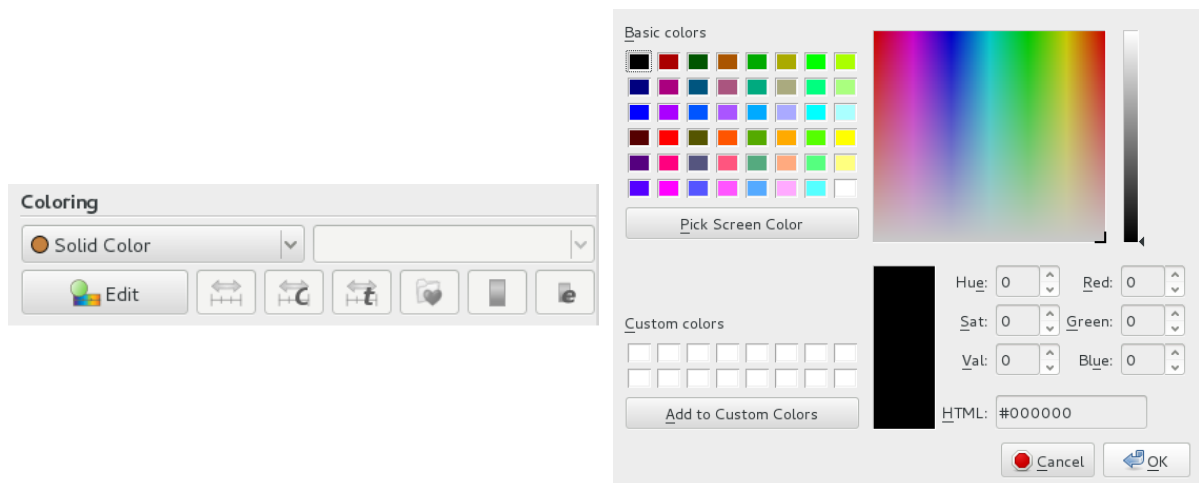


Figure III.58: Glyph coloring.

The result should look like Figure III.59.

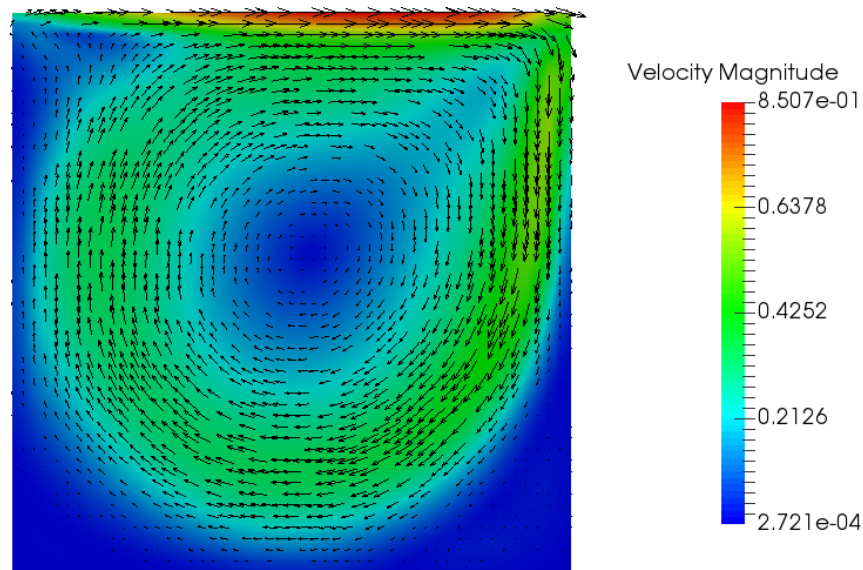


Figure III.59: Contour plot of the velocity with 2D glyphs.

To make it possible to create and locate the streamlines with regard to the Cavity, you are going to create a combined image showing the streamlines superimposed on top of the mesh.

First, create the streamlines. With **CellDatatoPointData** selected in the Pipeline Browser, click on **Filters** > **Common** > **Stream Tracer** in the top menu. The **StreamTracer** object is then added under **CellDatatoPointData** in the Pipeline Browser. Keep the **CellDatatoPointData** object selected and visible (eye icon in bold next to the object). In the Object Inspector, select the **Display** tab. In the **Coloring** category, choose **Solid Color** in the **Color by** drop-down list. In the **Style** category, change the **Representation** to **Wireframe** and decrease the **Opacity** to 0.1 (Figure III.60).

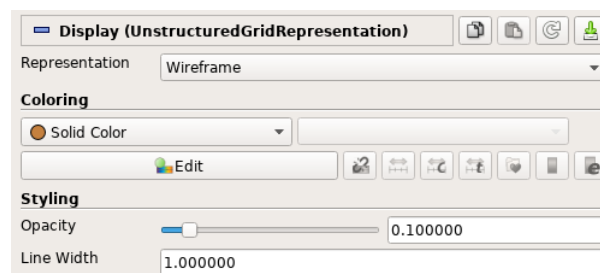


Figure III.60: Selecting the opacity.

The mesh lines displayed in the **ParaView scene Viewer** should be painted in faint black colour.

Next, select the **StreamTracer1** object in the Pipeline Browser. In the **Object Inspector**, select the **Properties** tab and modify the default settings for **Seeds**. Select **Point Source** for the **Seed Type**, and modify the **X** and **Y** coordinates of the seed point to 0.15 and 0.05, respectively. Request 60,000 points (**Number of Points**) and a radius of 1.0 (**Radius**), as shown in Figure III.61 below. Press **Apply** to validate your changes.

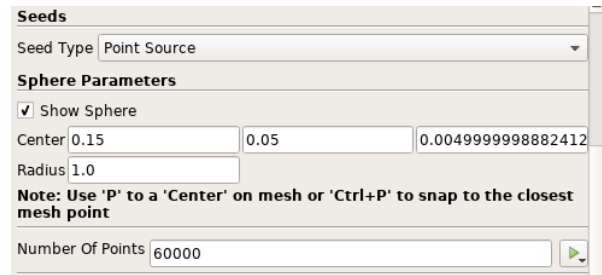


Figure III.61: Selecting the streamlines settings.

In the **Display** tab, choose **Velocity** and **Magnitude** from the **Color by** drop-down lists of category **Color** and visualise the streamlines coloured by velocity magnitude, on top of the computational mesh (Figure III.62).

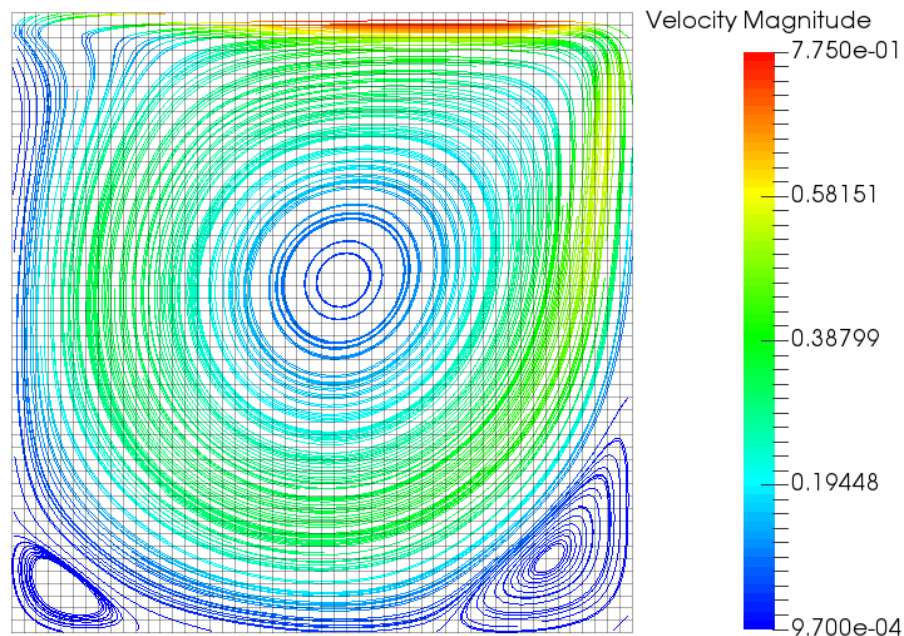


Figure III.62: Streamlines coloured by velocity magnitude superimposed on the mesh.

In addition to the general circular motion which had been inferred from the contour plots of velocity components, the streamlines now reveal two recirculation pockets in the bottom corners of the Cavity.

To further compare the calculated data with the available data from [4], create line plots of the X and Y velocities along the Y -axis and X -axis profiles which were set in the code_saturne GUI. Using the menu **File** **Open ParaView File**, import both the `XVel.YaxisCentreLine.csv` and the `YVel.XaxisCentreLine.csv` files. To read in the data and ensure that the velocities are correctly interpreted as real numbers by ParaView, in the Properties tab, define the **Field Delimiter Characters** as **','**: a comma. Also, select **Merge Consecutive Delimiters** (Figure III.63).

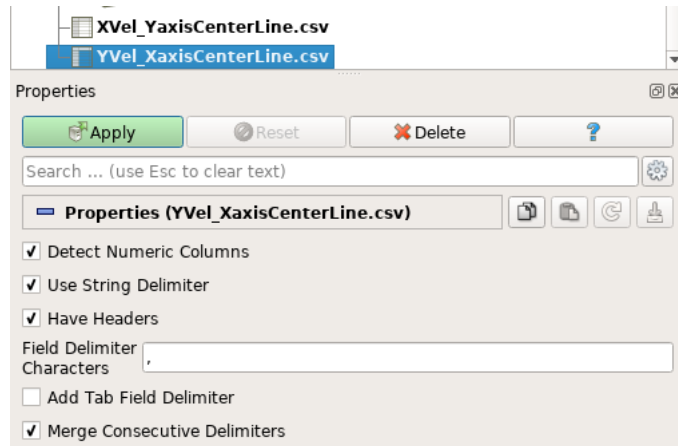


Figure III.63: Specifying the velocity profiles.

Go to the **Information** tab (if it doesn't appear, you can enable it by selecting **View** > **Windows** > **Information**) and verify that all the data arrays are read in as **double**. The steps to create and label the graphs are similar to those already detailed for the graphs of the **monitoring points** data and they are not repeated here.

For direct comparisons with the plots from [4], for the graphs of X velocity, plot the Y coordinate as a function of **Velocity[0]**. For the graphs of Y velocity, plot **Velocity[1]** as a function of the X coordinate. The reference data provided in [4] for the fine mesh results (129x129) is listed in Section 6. The data can be copied to a .csv file which is then imported in ParaView at the same time as the `XVel_YaxisCentreLine.csv` and the `YVelXaxisCentreLine.csv` files. Set the plots so that the code_saturne and the reference results are visualised in the same view, and display the reference points with a marker rather than a line. Each data set can then be compared directly with the reference results (Figure III.64).

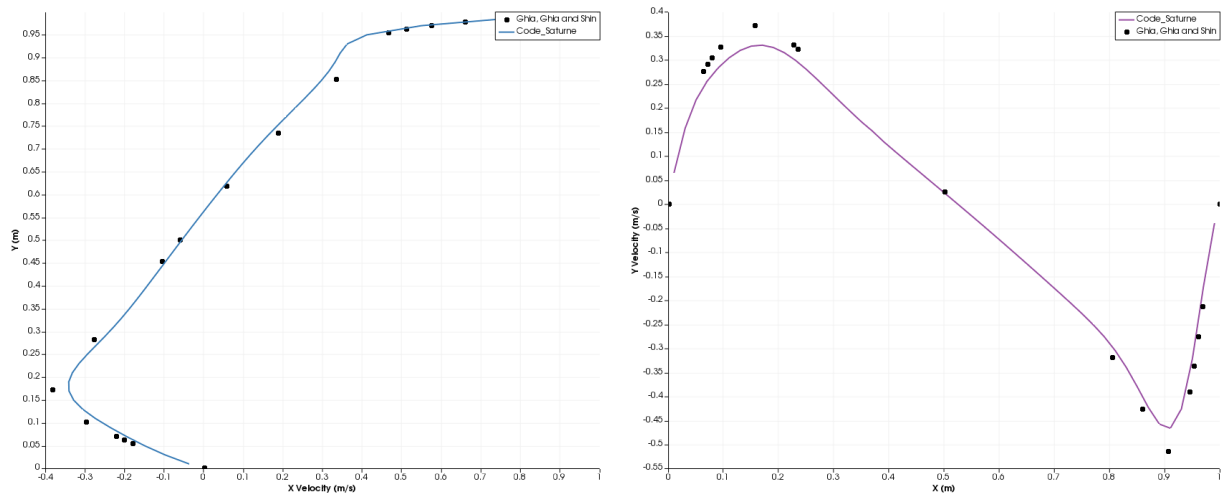


Figure III.64: Comparison between code_saturne (solid lines) and reference [4] results (circles). Y coordinate versus X velocity (left) and Y velocity versus X coordinate (right).

Overall, good agreement is obtained with the reference results [4], even though the results with code_saturne were obtained on a coarser mesh. Running on a finer mesh would make it possible to capture the velocity extremas with increased accuracy.

5 References

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Kitware, 2015, ISBN 978-1930934306

6 Reference Data from [4]

To make it easier to replicate the comparative plots of the code_saturne and reference results, the data from [4] (Tables I and II) at $Re = 1000$ is reproduced in Figure III.4 below. The reference results listed in [4] were obtained on a fine, 129×129 mesh.

Y (m)	U _x (m/s)	X (m)	U _y (m/s)
1.00000	1.00000	1.00000	0.00000
0.97660	0.65928	0.96880	-0.21388
0.96880	0.57492	0.96090	-0.27669
0.96090	0.51117	0.95310	-0.33714
0.95310	0.46604	0.94530	-0.39188
0.85160	0.33304	0.90630	-0.51550
0.73440	0.18719	0.85940	-0.42665
0.61720	0.05702	0.80470	-0.31966
0.50000	-0.06080	0.50000	0.02526
0.45310	-0.10648	0.23440	0.32235
0.28130	-0.27805	0.22660	0.33075
0.17190	-0.38289	0.15630	0.37095
0.10160	-0.29730	0.09380	0.32627
0.07030	-0.22220	0.07810	0.30353
0.06250	-0.20196	0.07030	0.29012
0.05470	-0.18109	0.06250	0.27485
0.00000	0.00000	0.00000	0.00000

Table III.4: X velocity versus Y at the vertical mid-plane and Y velocity versus X at the horizontal mid-plane. Data reproduced from [4]. $Re = 1000$. 129×129 mesh.