Final: Incompressible, Laminar Flow over a Rectangular Cavity

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1 Problem Description

Forty five years ago, Mehta and Lavan published a paper on the numerical investigation of flow over a rectangular cavity at low Reynolds numbers [1]. This relatively simple geometry provides tremendous insight into the physics of flow separation, an important flow feature in many applications. A numerical 2D planar model of these incompressible, laminar flows is developed here. In particular, the predicted flow structure (streamline pattern, eddies) and velocity profiles are investigated for a variety of aspect ratios (AR) and Reynolds numbers (Re).

	internal	lid	fixedWalls
U [m/s]	(0 0 0)*	(1 0 0)*	(0 0 0)*
p [m^2/s^2]	0*	zeroGradient	zeroGradient
ε [m^2/s^3]	0.000765*	0.000765^{*e}	0.000765^{*e}
k [m^2/s^2]	0.00325*	0.00325^{*k}	0.00325^{*k}
ν_t [m^2/s]	0*	0*	0*

Table 1: Initial conditions for simulation (*: uniform fields, ^{e}: epsilonWallFunction, ^{k}: kqRWallFunction)

2 Numerical Solution Approach

The pisoFoam solver from OpenFOAM 2.3.0 was used to model the solution of this problem. pisoFoam is a transient solver for incompressible flow which supports multiple forms of turbulence modelling. A Reynolds-average simulation (RAS) turbulence model is employed with a standard $k-\varepsilon$ model. Five cases were investigated: a base case with AR=0.5 and Reynolds number (Re) of 100, and additional cases of AR=0.5 with Re=1 and 2000 for AR=0.5, and AR=2.0 and 5.0 for Re=100. A Python script was created to generate the initial conditions and geometry for each case.

The solver is initialized with the initial conditions described in Table 1. Additionally, the boundary field for the inlet and outlet boundaries are set to "zeroGradient" for all of the initial fields and, the boundary field for frontAndBack is set to "empty" for all initial fields, turning this into a 2D problem. The geometry for this problem consists of a channel of length 10 m and height 1 m. A cavity is placed just below the channel and has a width of 1 m and a depth of AR. The script also generated the nonuniform mesh for this geometry using the blockMesh tool.

This mesh was divided into four regions: the left half of the channel, the right half of the channel, the center of the channel, and the cavity. For the base case, both the left and right halves of the channel were split into grids of 50x50 in the x, y direction, and also used "simpleGrading" to grade the meshes to make them denser near the center of the domain. The center of the channel was also split into grids of 50x50 in the x, y direction. The cavity for the base case was split into grids of 50x25 in the x, y direction and created a uniform mesh.

Name	x	y	simpleGrading
Left channel	M	M	(M^{-1} 1 1)
Right channel	M	M	(M 1 1)
Central channel	M	M	(1 1 1)
Cavity	M	M*AR	(1 1 1)

Table 2: Mesh configuration algorithm (M=50, AR=0.5 for base case)

The resultant mesh for the base case can be see in Figure 2. The domain of the problem was then split on to four CPUs using the decomposePar tool, and the pisoFoam solver was called with the MPI option. The solver than solved the system for 360 seconds and reconstructed the domain using the reconstructPar tool.

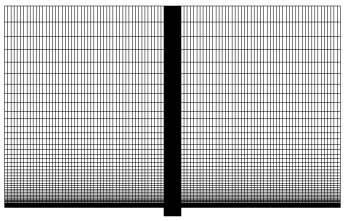

Fig. 1: Generated grid for the AR=0.5 cases

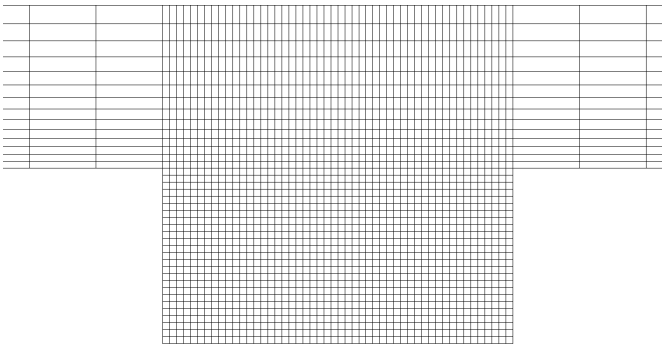

Fig. 2: Closeup on the cavity generated grid for the AR=0.5 cases

3 Results Discussion

4 Conclusion

References

[1] Mehta, U. B., and Lavan, Z., 1969. "Flow in a two-dimensional channel with a rectangular cavity". *Journal of Applied Mechanics,* **36**(4), pp. 897–901.

Appendix A: Python Code

```
import subprocess
import os


def inplace_change(filename, old_string, new_string):
    with open(filename) as f:
        s = f.read()

    if old_string in s:
        # print 'Changing "{old_string}" to "{new_string}"'.format(**locals())
        s = s.replace(old_string, new_string)
        with open(filename, 'w') as f:
            f.write(s)
    # else:
        # print 'No occurances of "{old_string}" found.'.format(**locals())


def subprocess_cmd(command):
    process = subprocess.Popen(command, stdout=subprocess.PIPE, shell=True)
    proc_stdout = process.communicate()[0].strip()
    # print proc_stdout


def generate_folders(ARs, Res):
    for AR, Re in zip(ARs, Res):
        run = "Run" + str(AR) + '-' + str(Re)
        if not os.path.exists(run):
            command = "cp -rf base/ " + run + "/; "
            subprocess_cmd(command)

    print ('Folders generated.')


def create_mesh_file(path, AR, Re):
    M = 50.

    YMESH    = str(int(M * AR))
    INV_GRADING = str(4. / M)
    GRADING = str(M / 4.)
    MESH     = str(int(M))
    AR       = str(-AR)

    inplace_change(path, 'AR',             AR)
    inplace_change(path, 'XMESH',        MESH)
    inplace_change(path, 'YMESH',       YMESH)
    inplace_change(path, 'INV_GRADING', INV_GRADING)
    inplace_change(path, 'GRADING',   GRADING)
    inplace_change(path, 'MESH',         MESH)


def create_properties_files(path, AR, Re):
    d = 10.           # characteristic size of domain
    NU = str(d / Re)

    inplace_change(path, 'NU_VAR', NU)


def update_dimensions(ARs, Res):
    for AR, Re in zip(ARs, Res):
        run = "Run" + str(AR) + '-' + str(Re)
        path = run + '/constant/polyMesh/blockMeshDict'
        create_mesh_file(path, AR, Re)

        path = run + '/constant/transportProperties'
        create_properties_files(path, AR, Re)

    print ('Config generated.')
```

```
68
69
70 def run_simulations(ARs, Res):
71     for AR, Re in zip(ARs, Res):
72         run = "Run" + str(AR) + '-' + str(Re)
73         if not os.path.exists(run + '/log'):
74             print(run + ' running now.')
75             command = "hdiutil attach -quiet -mountpoint $HOME/OpenFOAM OpenFOAM.sparsebundle; "
76             command += "sleep 1; "
77             command += "source $HOME/OpenFOAM/OpenFOAM-2.3.0/etc/bashrc; "
78             command += "cd " + run + "; "
79             command += "blockMesh; "
80             command += "decomposePar; "
81             command += "mpirun -np 4 pisoFoam -parallel > log; "
82             command += "reconstructPar; "
83             command += "streamFunction; "
84             # command += 'paraFoam --script="../paraFoam.py" '
85
86             subprocess_cmd(command)
87         print(run + ' complete.')
88
89     print('Simulations complete.')
90
91
92 def main(ARs, Res):
93     print('Running ARs ' + str(ARs) + ' with Res ' + str(Res) + '.')
94     generate_folders(ARs, Res)
95     update_dimensions(ARs, Res)
96     run_simulations(ARs, Res)
97     # generate_plots(ARs, Res)
98     print('Done!')
99
100 if __name__ == "__main__":
101     # Base case
102     ARs = [  0.5]
103     Res = [100.0]
104     #          o                      Broken=x Working=o
105     main(ARs, Res)
106
107     # Additional cases
108     ARs = [0.5,    0.5,   2.0,   5.0]
109     Res = [1.0, 2000.0, 100.0, 100.0]
110     # #        x       o      o      o  Broken=x Working=o
111     main(ARs, Res)
```

Listing 1: Code to create solutions

```
1  #### import the simple module from the paraview
2  from paraview.simple import *
3  import sys
4  #### disable automatic camera reset on 'Show'
5  paraview.simple._DisableFirstRenderCameraReset()
6
7  # get active source.
8  cavityClippedfoam = GetActiveSource()
9
10 # get active view
11 renderView1 = GetActiveViewOrCreate('RenderView')
12 # uncomment following to set a specific view size
13 # renderView1.ViewSize = [1054, 790]
14
15 # get color transfer function/color map for 'p'
16 pLUT = GetColorTransferFunction('p')
17 pLUT.RGBPoints = [0.0, 0.231373, 0.298039, 0.752941, 5e-17, 0.865003, 0.865003, 0.865003, 1e-16, 0.705882, 0.0156863,
18 pLUT.ScalarRangeInitialized = 1.0
19
20 # show data in view
21 cavityClippedfoamDisplay = Show(cavityClippedfoam, renderView1)
22 # trace defaults for the display properties.
```

```
cavityClippedfoamDisplay.ColorArrayName = ['POINTS', 'p']
cavityClippedfoamDisplay.LookupTable = pLUT
cavityClippedfoamDisplay.ScalarOpacityUnitDistance = 1.0844426982393176
cavityClippedfoamDisplay.SelectInputVectors = ['POINTS', 'U']
cavityClippedfoamDisplay.WriteLog = ''

# reset view to fit data
renderView1.ResetCamera()

# show color bar/color legend
cavityClippedfoamDisplay.SetScalarBarVisibility(renderView1, True)

# get opacity transfer function/opacity map for 'p'
pPWF = GetOpacityTransferFunction('p')
pPWF.Points = [0.0, 0.0, 0.5, 0.0, 1e-16, 1.0, 0.5, 0.0]
pPWF.ScalarRangeInitialized = 1

# change representation type
cavityClippedfoamDisplay.SetRepresentationType('Surface LIC')

# set scalar coloring
ColorBy(cavityClippedfoamDisplay, ('POINTS', 'streamFunction'))

# rescale color and/or opacity maps used to include current data range
cavityClippedfoamDisplay.RescaleTransferFunctionToDataRange(True)

# show color bar/color legend
cavityClippedfoamDisplay.SetScalarBarVisibility(renderView1, True)

# get color transfer function/color map for 'streamFunction'
streamFunctionLUT = GetColorTransferFunction('streamFunction')
streamFunctionLUT.RGBPoints = [-2.037569999694824, 0.231373, 0.298039, 0.752941, -0.9894677493721247, 0.865003, 0.865
streamFunctionLUT.ScalarRangeInitialized = 1.0

# get opacity transfer function/opacity map for 'streamFunction'
streamFunctionPWF = GetOpacityTransferFunction('streamFunction')
streamFunctionPWF.Points = [-2.037569999694824, 0.0, 0.5, 0.0, 0.058634500950574875, 1.0, 0.5, 0.0]
streamFunctionPWF.ScalarRangeInitialized = 1

# Properties modified on renderView1
renderView1.Background = [1.0, 1.0, 1.0]

# Properties modified on renderView1
renderView1.OrientationAxesVisibility = 0

# Properties modified on cavityClippedfoamDisplay
cavityClippedfoamDisplay.ColorMode = 'Multiply'

# hide color bar/color legend
cavityClippedfoamDisplay.SetScalarBarVisibility(renderView1, False)

# Properties modified on cavityClippedfoamDisplay
cavityClippedfoamDisplay.EnhanceContrast = 'LIC and Color'

#change interaction mode for render view
renderView1.InteractionMode = '2D'

#### saving camera placements for all active views

# current camera placement for renderView1
renderView1.InteractionMode = '2D'
renderView1.CameraPosition = [-6.546626850823488e-06, 0.024711792637900302, 0.29411509449255]
renderView1.CameraFocalPoint = [-6.546626850823488e-06, 0.024711792637900302, 0.004999999888241291]
renderView1.CameraParallelScale = 0.0768830580193085

#### uncomment the following to render all views
SaveScreenshot('/Users/localmin/code/MAE-219/cavityClipped/test_image.png', magnification=1, quality=100, view=render
sys.exit()
```

Listing 2: Code to generate pretty plots using paraFoam