Lifex-CFD-tests

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测试1

Beltrami flow benchmark problem

可生成默认的参数文件：lifex_test_fluid_dynamics_cube.prm

./lifex_test_fluid_dynamics_cube -g

可修改参数文件，然后运行：

./lifex_test_fluid_dynamics_cube -f lifex_test_fluid_dynamics_cube.prm

We set $T = 10^{-5}$ s, $\Delta t = 10^{-6}$ s, and perform a convergence test in space for h = 0.085, 0.17, 0.34, 0.68, 1.36 m (corresponding to a number of mesh refinements equal to 7, 6, 5, 4, 3, respectively), with Q2 − Q1 finite elements and without any stabilization.

测试2 Fluid dynamics in a compliant cylinder with a moving obstacle (Test II)

./lifex_fluid_dynamics -g -b "Inlet" "Outlet"

圆柱的侧向wall，预定义no-slip边界条件。因此，无需将其包含在边界标记列表内（如下）。圆柱长度L=0.1m，半径R=0.01m，deal.II网格生成5次细化的hexahedral网格（见表2的网格细节信息）。在参数文件中设置如下参数：

```
subsection Mesh and space discretization
   set Mesh type                   = Cylinder
   set Element type                = Hex
   set Number of refinements = 5

   subsection Cylinder
     set Radius = 0.01
     set Length = 0.1
   end
end
```

Test case	Type	# elements	# vertices	h_{min} [mm]	h_{avg} [mm]	h_{max} [mm]	q_{min}	q_{avg}	q_{max}
I (Beltrami flow, Section 4.1)	Hex	-	-	-	-	-	1	1	1
II (cylinder, Section 4.2)	Hex	81920	85345	1.64	1.75	1.91	3.11	4.02	5.38
III (aorta, Section 4.3)	Tet	2915690	543089	0.08	0.8	2.9	1.04	2.96	16.83
IV (left atrium, Section 4.4)	Tet	2438278	389484	0.28	0.8	1.3	1.00	1.54	3.08
V (Taylor-Green, Section 4.5)	Hex	32^3	35937	0.34	0.34	0.34	1	1	1
	Hex	64^3	274625	0.17	0.17	0.17	1	1	1

测试2

边壁No-slip边界条件(tag 0)，入口为Dirichlet BC (tag 1)，出口为各向同性Neumann BC (tag 2)。入口流速分布剖面为抛物型，脉冲时间函数的g_{min}=0 m^3/s， g_{max}=2.5x10^{-4}和周期

入口的Re数 $$Re = \frac{2\rho g_{max}}{\mu \pi R} = 4812$$

测试2

```
subsection Boundary conditions
  set No-slip tags   = 0

  subsection Inlet
    set Tags                          = 1
    set Type of boundary condition = Dirichlet
    subsection Dirichlet
      set Time evolution     = Pulsatile
      set Space distribution = Parabolic
      subsection Pulsatile
        set Minimum value = 0.0
        set Maximum value = 2.5e-4
        set Period        = 0.8
      end
    end
  end

  subsection Outlet
    set Tags                          = 2
    set Type of boundary condition = Neumann
    subsection Neumann
      set Time evolution = Constant
      subsection Constant
        set Value = 0.0
      end
    end
  end
end
```

测试2

计算域边界移动根据从vtp文件读取的位移设置。该文件包含计算域边界的表面和一系列的9个位移场，从等时间采样获取（每0.1s一次），位移场为:

$$\hat{d}^{\partial\Omega}(\hat{x},t)=C\frac{z(L-z)}{\sqrt{\hat{x}^2+\hat{y}^2}}\sin\left(\frac{2\pi t}{T}\right)(\hat{x},\hat{y},0)^T$$

在ALE框架下求解不可压缩NS方程，联合边界位移的升力问题(1)。使用和谐升力，使用AMG预处理的CG法求解:

```
subsection Arbitrary Lagrangian Eulerian
  set Active                            = true
  set Import displacement from file = true

  subsection Input file
    set Boundary displacements filename       =
   displacement_cylinder.vtp
    set Boundary displacement field basename = d
    set Time subintervals                    = 8
    set Time subinterval duration            = 0.1
    set Interpolation mode                   = Splines
  end

  subsection Lifting
    set Lifting operator = Harmonic
    set Tags Dirichlet   = 0, 1, 2
  end
end
```

测试2

计算域中，移动的表面障碍物表示一个浸没的理想阀门叶片（使用RIIS方法）。

阀门的封闭配置及其位移场openingField存储在文件cylinder_plane_closed.vtp。

RIIS方法使用的参数有：ε=3mm，R=10^4 kg/(m.s)。阀门在封闭配置中启动，在$t \in [0.15, 0.25]$开启，在$t \in [0.25, 0.55]$ s时段保持开启，在时段$t \in [0.55, 0.65]$ s关闭，之后保持关闭。

```
subsection Resistive Immersed Implicit Surface
  set Active                           = true
  set Use surface velocity             = false
  set Surface labels                   = surface
  set Immersed surfaces basenames      = cylinder_plane_closed
  set Move surfaces with ALE           = true
  set Displacement names               = openingField
  set Epsilons                         = 0.003
  set Resistances                      = 10000

  subsection Displacement law
    set Displacement laws = Prescribed

    subsection Prescribed
      set First ramp: start time  = 0.15
      set First ramp: end time    = 0.25
      set Second ramp: start time = 0.55
      set Second ramp: end time   = 0.65
    end
  end
end
```

测试2

问题求解，使用半隐式处理对流项，因此问题是线性的。使用单个Newton迭代，使用如下参数设置：

Backward Differentiation Formulas (BDF)

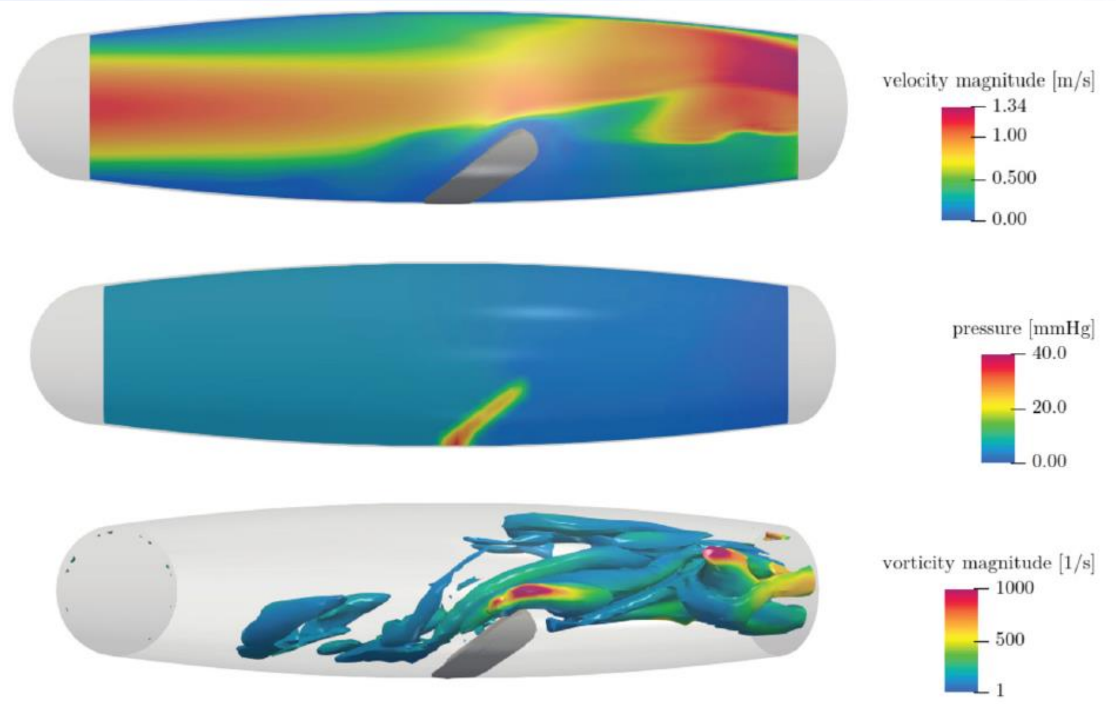
```
subsection Time solver
  set BDF order                      = 1
  set Non-linearity treatment = Semi-implicit
  set Initial time                   = 0
  set Final time                     = 0.8
  set Time step                      = 1e-4
end

subsection Non-linear solver
  set Linearized = true
end
```

测试2

心血管CFD模拟理想血管，使用浸没阀门的ALE方法。在t=0.26s时刻的模拟结果如图4。此时，阀门处于打开位置，图中灰色表示RIIS项的Dirac delta：

$$\{\boldsymbol{x} \in \Omega_t : |\varphi(\boldsymbol{x})| < \varepsilon\}$$



相干涡旋结构

Fig. 4. Test II. Flow results at $t = 0.26$ s: velocity magnitude (top) and pressure (center) distributions on a median slice, and Q-criterion contours (bottom, $Q = 1000/s^2$) colored by the vorticity magnitude. In gray, the region occupied by the valve. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

测试3 a vascular case (Test III)

1名健康男性的aorta的一部分，在J.F.J. LaDisa et al., 2011文献中也模拟过。

网格如图5。相关的入口边界条件从Vascular Model Repository中获取。网格使用vmtk前处理，再转换为lifex-cfd支持的msh格式。

计算域包含1个入口（对应aortic root section）和4个出口（对应supra-aortic arteries and abdominal aorta）。计算域不移动，也没有阀门。

入口施加Dirichlet边界条件。

测试3

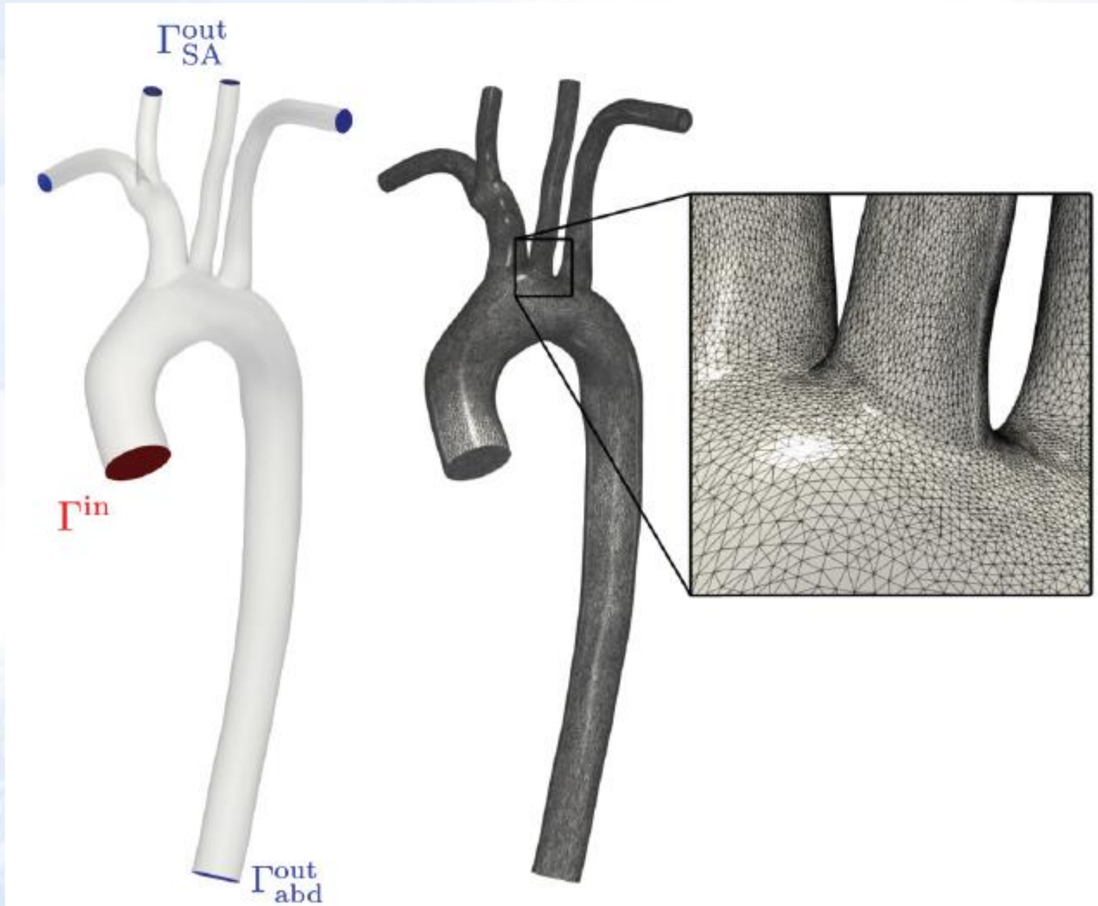


Fig. 5. Test III. Computational domain and mesh, obtained from the Vascular Model Repository

测试3

a vascular case (Test III)

```
./lifex_fluid_dynamics -g  \
   -b "Aortic root" "Right subclavian" \
   "Right common carotid" "Left common carotid" \
   "Left subclavian" "Abdominal aorta"
```

测试3

a vascular case (Test III)

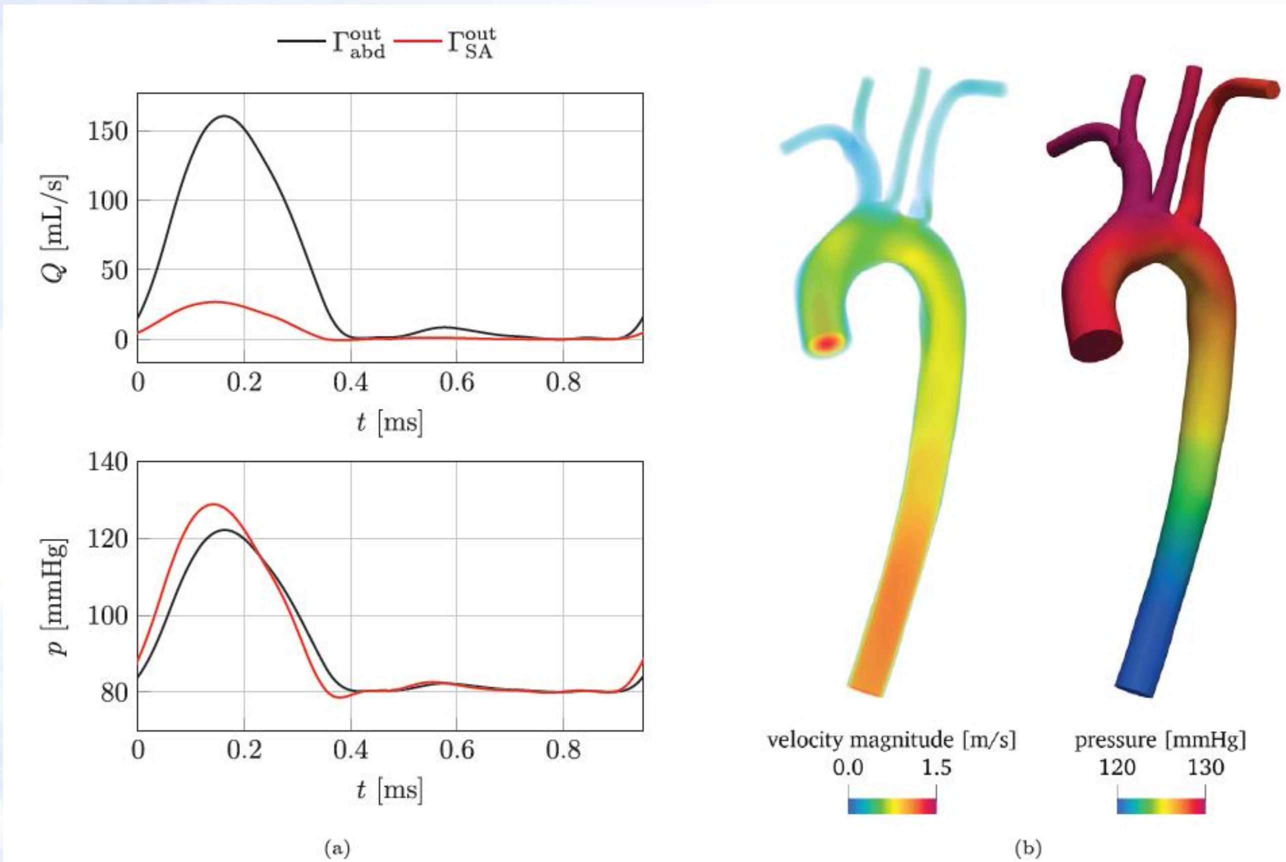


Fig. 6. Test III. (a) Flowrate and average pressure on the supra-aortic and abdominal outlets during the last heartbeat of the simulation. (b) Volume rendering of the blood velocity magnitude and pressure at time t = 0.15 s of the last simulated cycle.

测试4　　a patient-specific left atrium geometry (左心房)

$ ./lifex_fluid_dynamics -g -b "Pulmonary veins" "Mitral valve"

如图7a，左心房有4个入口，1个出口，the endocardial wall. 图7b是使用vmtk生成的左心房的四面体网格。

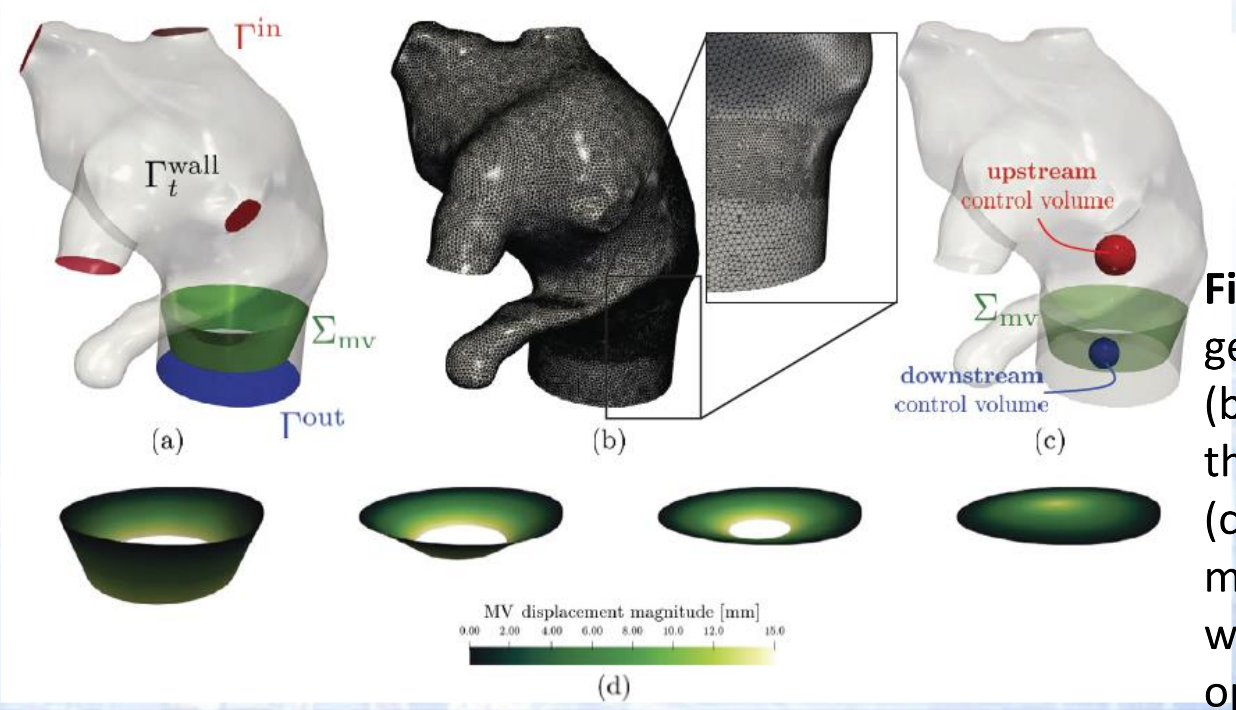


Fig. 7. Test IV. (a): left atrium geometry, with boundary portions; (b) tethraedral mesh refined on the proximity of the mitral valve; (c) control volumes upstream the mitral valve; (d) mitral valve warped by its displacement (from open to closed configuration).

测试4

边界条件

As boundary data, we prescribe Neumann boundary conditions on the inlet pulmonary veins sections and on the section downwind the mitral valve.

We simulate 3 heartbeats of period …

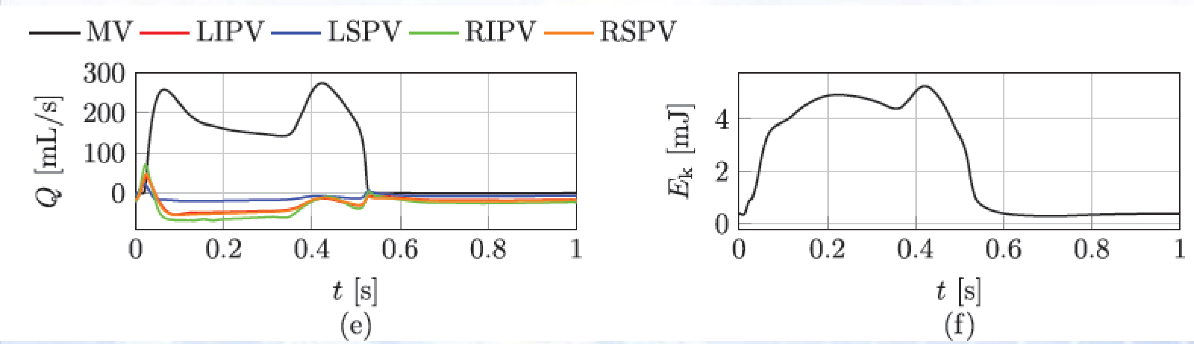


图8

测试4　　如图9，显示了速度大小与Q准则提取涡旋的体渲染图。

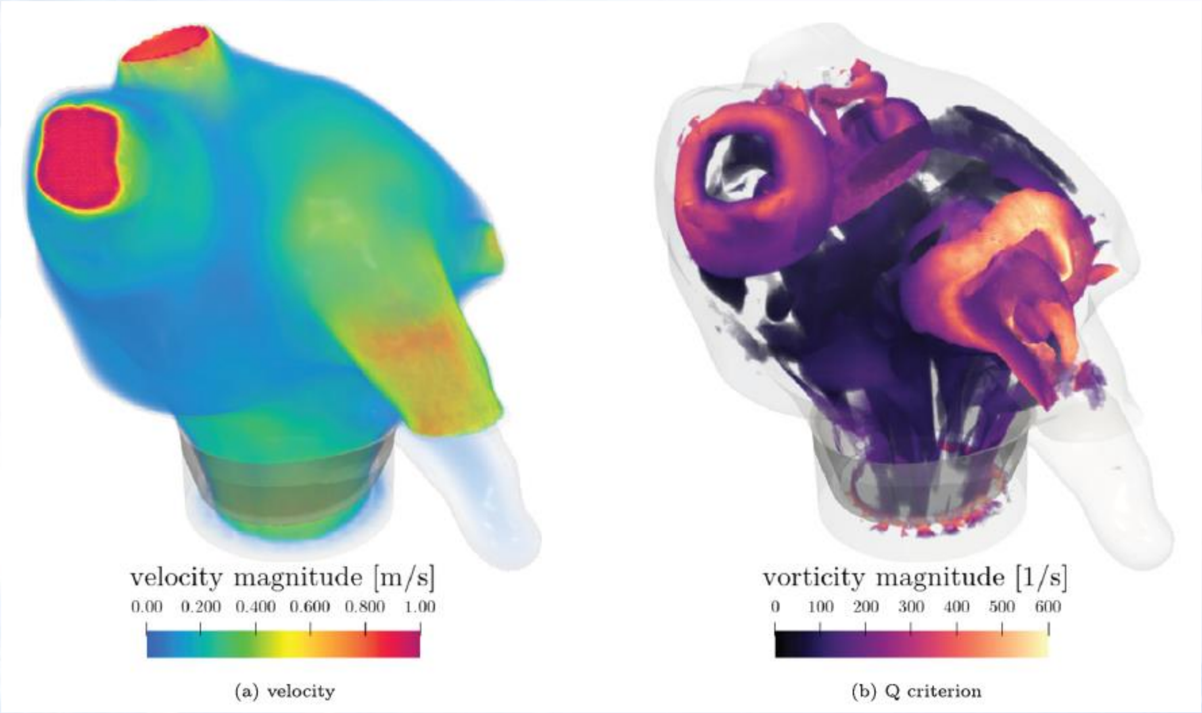


Fig. 9. Test IV. 3D visualizations of left atrium simulation at the early-wave peak. (a) volume rendering of velocity magnitude; (b) volume rendering of Q criterion (Q= $50/s^2$) colored according to vorticity magnitude.

测试5

A turbulent benchmark: the Taylor Green Vortex benchmark (Test V)

We use quadratic FEs for velocity and pressure (Q2-Q2), time-step size equal to 0.002 s and the VMS-LES method [114,116] both to stabilize the problem and to model turbulence (see Section 2.3).

计算量太大，无法在一般机器上执行！