Design of Integrated Microrobotic Fish

Presentation 4 - Physical Model (Improving) & COMSOL Simulation (2D)

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Contents

COMSOL Simulation (2D)

From KLayout to AutoCAD

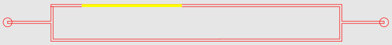


Figure: The whole layout.

From KLayout to AutoCAD

Details

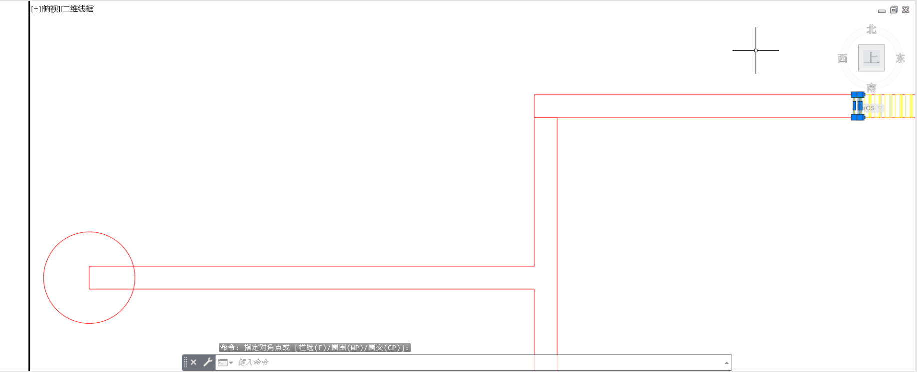


Figure: Details.

AutoCAD Processing

Steps

1. Erase the redundant boundaries.
2. Erase the up, left, and right edges of the tiny rectangles.
3. Erase the down edges of the tiny rectangles and redraw the startpoints and endpoints of the edges.

AutoCAD Processing

AutoLISP/Visual Lisp Code

```
; Inspired by https://forums.autodesk.com/t5/visual-lisp-autolisp-and-general/get-x-y-z-coordinates-of-vertices-of-multiple-3d
↪  polylines/m-p/2822802/highlight/true#M292893
(defun c:test (/ ss cnt fn obj lst1 str)  ; Check parameters first, otherwise "错误: 参数类型错误: lselsetp nil" or "错误:
↪  参数太多"
  (setq ss (ssget ":E" '((0 . "LINE")))  ; Exported electrodes are lines, not polylines; ":E" indicates selection set needed
   ↪  before running
    cnt -1
    fn (open "D:\\Documents\\Programming\\AutoLISP\\coordlist.txt" "w")  ; File operations are not necessary, just for checki
ng
  )
  (repeat (sslength ss)
    (setq obj (vlax-ename->vla-object (ssname ss (setq cnt (1+ cnt)))))
    (if
      (= "AcDbLine" (vlax-get obj 'Objectname))  ; Alternatively ((eq (vla-get-ObjectName obj) "AcDbLine")
      (progn
        (setq sp (vlax-get obj 'StartPoint)  ; Alternatively (setq sp (vlax-curve-getstartpoint obj))
          ep (vlax-get obj 'EndPoint)  ; Alternatively (setq ep (vlax-curve-getendpoint obj))
          ; Note that different from "AcDbPolyline", "AcDbLine" does not have "Coordinates", otherwise "错误: ActiveX
         ↪  服务器返回错误: 未知名称: "COORDINATES""
          str (strcat (rtos (car sp)) "," (rtos (cadr sp)) ";" (rtos (car ep)) "," (rtos (cadr ep)) ";")
          ; Here must be "cadr" rather than "cdr", otherwise "错误: 参数类型错误: numberp: (1300.0 0.0)"
          ; Remember don't concatenate str without initializing it by (setq str ""), otherwise "错误: 参数类型错误: stringp nil"
          mspace (vla-get-modelspace
            (vla-get-activedocument
              (vlax-get-acad-object)
            )
          )
        )
        (write-line str fn)
        (vla-addpoint mspace (vlax-3d-point sp))  ; (command "Point" sp ep)
        (vla-addpoint mspace (vlax-3d-point ep))  ; (vla-put -INSERTIONPOINT Obj mypoint) (vlax-put Obj 'INSERTIONPOINT
       ↪  mypoint)
        (vla-delete obj)  ; (command "Erase" obj)
      )
```

AutoCAD Processing

AutoLISP/Visual Lisp Code

```
        (progn  ; Exception
          (redraw)
          (redraw (vlax-vla-object->ename obj) 3)
          (alert (strcat "This entity (Handle ID " (vlax-get obj 'Handle) ") is not a Line"))
      )
    )
  )
  (close fn)
  (princ)
)
```

COMSOL Model

Global Definitions

Name	Expression	Value	Description
U0	0.001[mm/s]	1E-6 m/s	Mean inflow velocity
sigma_w	0.00123[S/m]	0.00123 S/m	Conductivity of the ionic solution
eps_r	80.2	80.2	Relative permittivity of the fluid
zeta	-0.120596[V]	-0.1206 V	Zeta potential
V0	0.1[V]	0.1 V	Maximum value of the AC potential
omega	2*pi[rad]*1000[Hz]	6283.2 Hz	Angular frequency of the AC potential
t	0[s]	0 s	Start time
D	1e-11[m^2/s]	1E-11 m^2/s	Diffusion coefficient of the solution
c0	1[mol/m^3]	1 mol/m^3	Initial concentration

Table: Parameters 1

COMSOL Model

Component

Geometry:

- Import: import from DXF file
- Split: split the tube and the part surrounded by the tube
- Delete Entities: delete the part surrounded by the tube
- Form Union

Materials:

Property	Variable	Value	Unit	Property group
Density	rho	1e3[kg/m^3]	kg/m^3	Basic
Dynamic viscosity	mu	1e-3[Pa*s]	Pa • s	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	sigma_w	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	eps_r	1	Basic

COMSOL Model

Component

- Laminar Flow (spf)
  - Wall 1
  - Inlet 1
  - Outlet 1
- Electric Currents (ec)
  - Electric Potential 1 (Large Electrodes) $V_0 = V0$
  - Electric Potential 2 (Small Electrodes) $V_0 = -V0$
- Transport of Diluted Species (tds)
  - Concentration 1
    $c_{0,c} = c0 * step1(y[1/m])\,\mathrm{mol/m^3}$
  - Outflow 1
    Show equation assuming Study 1, Stationary $\boldsymbol{n} \cdot D_i \nabla c_i = 0$
- Mesh
  - Size
  - Free Triangular 1

COMSOL Model

Study & Results

Study:

- Step 1: Stationary
- Step 2: Time Dependent
  - Time unit: s
  - Output times: range(0,0.125/60,0.5)
  - Tolerance: Physics controlled

Results:

- Velocity, streamlines: Streamline
- Electric potential: Contour
- Concentration: Surface & Streamline

Results

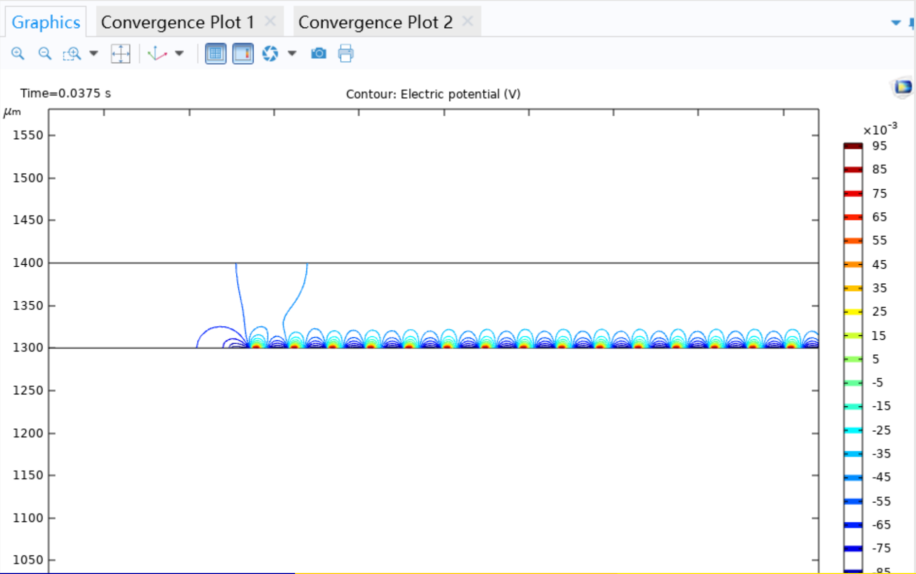
Velocity, streamlines

Results

Electric potential

Results

Electric potential



Physical Model

Reference

Reference:

Pham, Pascale, et al. "Numerical simulation of the electrical double layer based on the poisson-boltzmann models for ac electroosmosis flows." Excerpt from the Proceedings of the COMSOL Users Conference 2007 Grenoble. 2007.

"Double layer (surface science)." Wikipedia, The Free Encyclopedia. 16 February 2021, 14:33 UTC. Wikimedia Foundation, Inc. 16 Mar. 2021. <https://en.wikipedia.org/wiki/Double_layer_(surface_science)>.

"Stern layer." SEAS Soft Matter Wiki. 9 December 2011, 03:46 UTC. 16 Mar. 2021. <http://soft-matter.seas.harvard.edu/index.php/Stern_layer>

González, Antonio, et al. "Fluid flow induced by nonuniform ac electric fields in electrolytes on microelectrodes. II. A linear double-layer analysis." Physical review E 61.4 (2000): 4019.

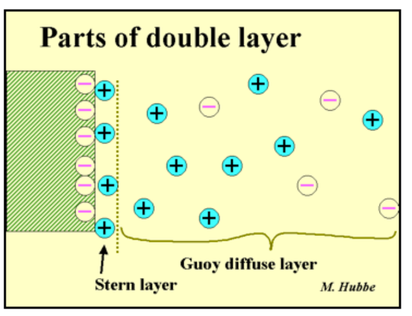
Physical Model

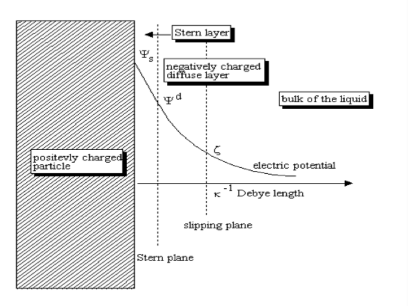
- Helmholtz: Predicted a constant differential capacitance; does not consider important factors including diffusion/mixing of ions in solution.
- Gouy-Chapman: The theory for a flat surface and a symmetrical electrolyte is usually referred to as the Gouy-Chapman theory.

  $$\sigma^d = -\sqrt{8\varepsilon_0\varepsilon_m CRT}\sinh\frac{F\Psi^d}{2RT}$$

  where σ^d is the electric charge in the diffuse layer and Ψ^d is the Stern potential.
  The Gouy-Chapman model fails for highly charged DLs (electrical double layers).
- Stern: Combining the Helmholtz model, giving an internal Stern layer, while some form a Gouy-Chapman diffuse layer.
  Assumes all significant interactions in the diffuse layer are Coulombic, and assumes dielectric permittivity to be constant throughout the double layer and that fluid viscosity is constant plane.

Physical Model





- In the case when electric potential over DL is less than 25 mV, the so-called Debye-Huckel approximation holds.

$$\Psi(r) = \Psi^d \frac{a}{r} \exp\left(-\kappa(r-a)\right)$$

Physical Model

COMSOL's approach

- The Navier-Stokes equations for incompressible flow describe the flow in the channels:

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} - \nabla \cdot \eta \nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T + \rho \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \nabla p = 0$$

$$\nabla \cdot \boldsymbol{u} = 0$$

  Here η denotes the dynamic viscosity (SI unit: kg/(m • s)), u is the velocity (SI unit: m/s), ρ equals the fluid density (SI unit: kg/m3), and p refers to the pressure (SI unit: Pa).

- Total stress components normal to the boundary:

$$\boldsymbol{n} \cdot [-p\boldsymbol{I} + \eta(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)] = 0$$

- Replace the thin electric double layer with the Helmholtz-Smoluchowski relation between the electroosmotic velocity and the tangential component of the applied electric field:

$$\boldsymbol{u} = \frac{\varepsilon_w \zeta_0}{\eta} \nabla_T V$$

  $\varepsilon_w = \varepsilon_0 \varepsilon_r$ denotes the fluid' s electric permittivity (F/m), ζ_0 is the zeta potential at the channel wall (V). This equation applies only on the wall.

Physical Model

COMSOL's approach

- The balance equation for current density:

$$\nabla \cdot (-\sigma \nabla V) = 0$$

  where σ denotes conductivity (S/m) and the expression within parentheses represents the current density ($\mathrm{A/m^2}$).

- The normal component of the electric field is zero:

$$-\sigma \nabla V \cdot \boldsymbol{n} = 0$$

- (Not necessary) The convection-diffusion equation describes the concentration of the dissolved substances in the fluid:

$$\frac{\partial c}{\partial t} + \nabla \cdot (-D \nabla c) = R - \boldsymbol{u} \cdot \nabla c$$

Thanks!