28 May 2015

A Study of Mixing in a Magnetohydrodynamic (MHD) Microfluidic Cell By Numerical Simulations

Fangping Yuan

Kakkattukuzhy M. Isaac
Missouri University of Science and Technology, isaac@mst.edu

A Study of Mixing in a Magnetohydrodynamic (MHD) Microfluidic Cell By Numerical Simulations

Fangping Yuan
K.M. Isaac
Mechanical and Aerospace Engineering
Missouri University of Science and Technology

227th ECS Meeting
Chicago Illinois,
May 24-28, 2015

Outline

- What is MHD and why MHD?
- Literature review in MHD microfluidics.
- Geometry configuration.
- Governing equations, boundary and initial conditions.
- Results.
- Conclusion.
- Future work.
- Acknowledgement.

What is MHD?

- MHD = Magnetohydrodynamics.
- Study the interaction between the electromagnetic force (Lorentz force) and fluid flow.
- Can be used for pumping and controlling highly conductive liquid metals and plasma.
- Also can be used in weakly conductive electrolyte solution in redox (reduced species-oxidized species) system. ECMHD (electrochemical magnetohydrodynamics)

Why MHD? (1)

- Great interest in Lab on a chip (LOAC) devices, which are small in size and can be used in diagnosis of illness, medical treatment, detection of chemicals and synthesis of materials.
- Rapid and efficient mixing is an important task among the various LOAC functions.
- How to accomplish mixing in micro devices? passive and active methods are being explored.

Why MHD? (2)

- Passive method: using specific channel geometry configurations to increase the interface area between fluids.
- Active method: introducing driving forces or mechanical components.
- Challenges: small size. difficult to manufacture.
- Electrostatic force: requires high electric potential which may introduce significant Joule heating. Bubble generation and electrode erosion are also drawbacks.
- Lorentz force, which can overcome these disadvantages, becomes favorable.

Literature Review in MHD microfluidics

- Can be used to induce the flow of weakly conductive electrolyte solution in redox MHD-based systems [1]. Experiments along with CFD simulations show that the flow velocity of μm/s or even mm/s is feasible by applying electric potential of ~1V and magnetic field strengths of ~0.5T [2-3].
- Can be used as micro-pumps [4-5].

[1] Sen. D, K.M. Isaac, Leventis. N. Investigation of transient redox electrochemical MHD using numerical simulations. *Int J heat mass Transf*. 2011, 54(25), 5368-5378.
[2] Leventis. N, Chan. M, Gao. X, Canalas. M, Zhang. P. Electrochemistry with stationary disk and ring-disk millielectrodes in magnetic fields. *J. Phys, Chem B*. 1998, 102(18), 3512-3522.
[3] Qian. S.; Bau. H.H. Magnetohydrodynamic flow of Redox electrolyte. *Physics of Fluids*. 2005, 17(6), 067105-067105-12.
[4] Lemoff. A.V., Lee, A.P. An Ac magnetohydrodynamic micro-pump. *Sensors and Actuators B*. 2000, 63(3), 178-185.
[5] Jang. J., Lee. S.S. Theoretical and experimental study of MHD (magnetohydrodynamic) micropump. *Sensors and Actuators B*. 2000, 80(1), 84-89.

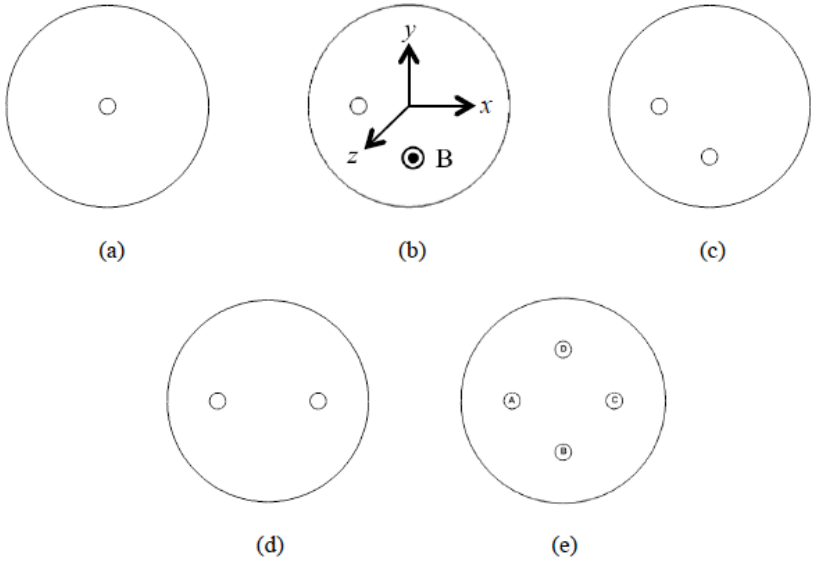
Literature Review in MHD mixing in microfluidics

- A theoretical study in MHD mixing in an annular micro-mixer in which the direction of flow reversed periodically [6].
- A simple rectangle MHD minute mixer has been studied by theoretical and experiment tools [7].
- Depending on the electrode placements and magnetic field orientation, secondary flows and complex chaotic advection can be generated to enhance the mixing efficiency [8,9].

[6] Gleeson. J.P., Roche. O.M., West. J., Gelb. A. Modelling annular micromixers. *SIAM J. APPL. MATH*. 2004, 64(4), 1294-1310.
[7] Bau. H.H., Zhong. J., Yi. M. A minute magnetohydrodynamic (MHD) mixer. *Sensors and Actuators B*. 2001, 79(2), 207-215.
[8] Rossi. L., Doorly. D., Kustrin. D. Lamination and mixing in three fundamental flow sequences driven by electromagnetic body forces. *Physical Review E*. 2012, 86(2), 026313-026313-14.
[9] Yi. M., Qian. S., Bau. H.H. A magnetohydrodynamic chaotic stirrer. *Journal of Fluid Mechanics*. 2002, 468, 153-177.

Geometry configuration used in this study

- A cylindrical cavity with cylindrical rods inside the cavity.
- Entire cavity side wall serves as counter electrode.
- Inner cylinders serve as working electrode.



Governing equations, boundary and initial conditions (1)

- Continuity, momentum and species conservation equations:

$$\nabla \cdot \bar{V} = 0.$$

$$\rho \frac{D\bar{V}}{Dt} = -\bar{\nabla} p + \mu \nabla^2 \bar{V} + \bar{F}_{\mathrm{L}}.$$

$$\frac{\partial C_i}{\partial t} + \bar{\nabla} \cdot (C_i \bar{V}) = \bar{\nabla} \cdot (D_i \bar{\nabla} C_i).$$

- Lorentz force:

$$\bar{F}_{\mathrm{L}} = \bar{J} \times B = -\sigma \bar{\nabla} \phi \times \bar{B}$$

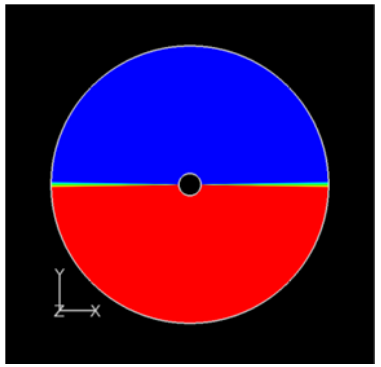
- Current density:

$$\bar{J} = F \sum_{i=1}^{m} z_i N_i = \underbrace{\bar{\nabla} \phi \frac{F^2}{RT} \sum_i z_i^2 D_i c_i}_{-\sigma}$$

Governing equations, boundary and initial conditions (2)

- Initial species concentration distribution:

$$C_1(x, y, 0) = \begin{cases} 0, & y > 0 \\ 1, & y < 0 \end{cases}.$$



- Boundary conditions:

$\bar{V}_{\text{wall}} = 0.$

$\phi = 0$ on the counter electrode.

$\phi = \phi_0 \sin(2\pi t / T)$ on the working electrode.

where T is the time period.

Mixing quality

- Mixing quality which is defined as [10]:

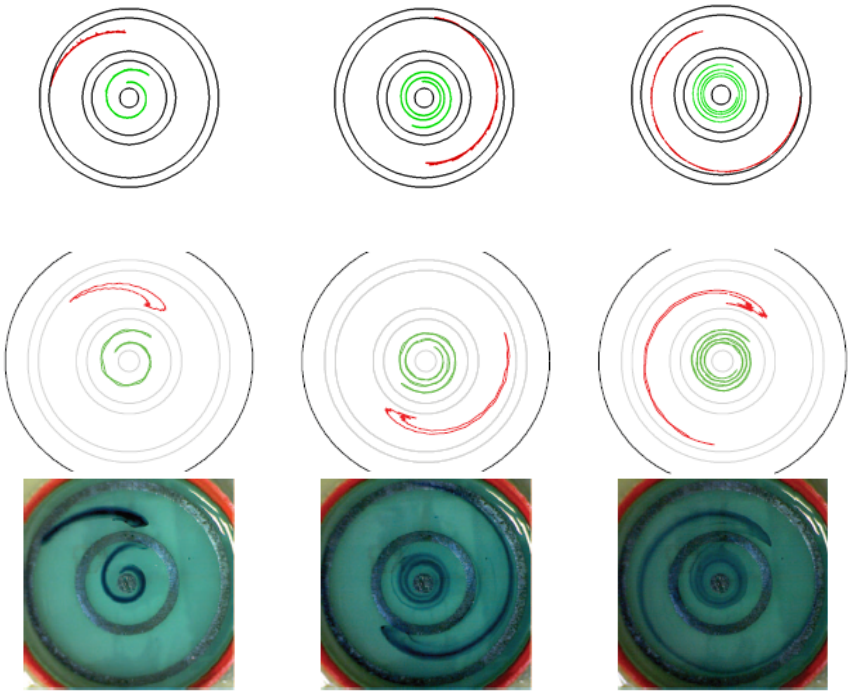
$$\alpha(t) = 1 - \frac{\delta^2(t)}{\delta^2(0)}.$$

- Where, $\delta^2(t)$ is the standard deviation of the dimensionless concentration distribution at time t:

$$\delta^2(t) = \oiint_S \left[C(x, y, t) - \overline{C}(t) \right]^2 dxdy.$$

[10] Qian. S. Bau. H.H. Magnetohydrodynamic stirrer for stationary and moving fluids. *Sensors and Actuator B*. 2005, 106(2), 859-870.

Result (1)
Simulation validation



Our numerical simulations of material lines, snapshots taken at t=50s, 110s and 170s

Numerical simulation and dye experiment, snapshots taken every 50s. From S. Dufour's paper [11]

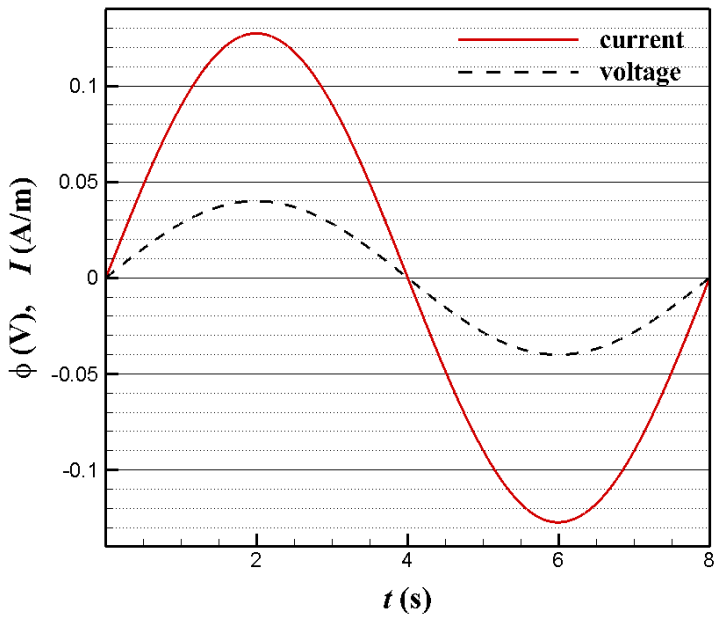
[11] Dufour. S., Vinsard. G., Mota. J.P., Saatdjian. E., *Physics of Fluids*. 2013, 25(10), 102001-102001-16.

Results (2)
Concentric cylinder, configuration (a)

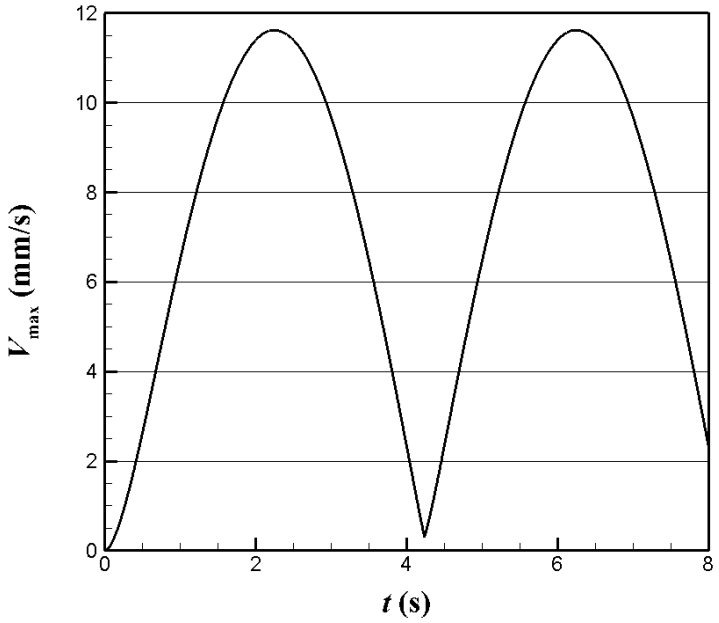
- In all simulations, 0.1M KCl solution has been chosen as the electrolyte.
- The electrical conductivity: σ=1.29 S/m.
- Diffusion coefficient $D=1.0\times10^{-11}$ m^2/s.
- Dynamic viscosity: μ=0.001003 kg/m-s.
- Magnetic field B is uniform and perpendicular to the x-y plane.
- Applied potential on the counter electrode is zero.
- Applied potential on working electrode is set as:

$$\phi = \phi_0 \sin(2\pi t / T)$$

Results (3)
Concentric cylinder, configuration (a)



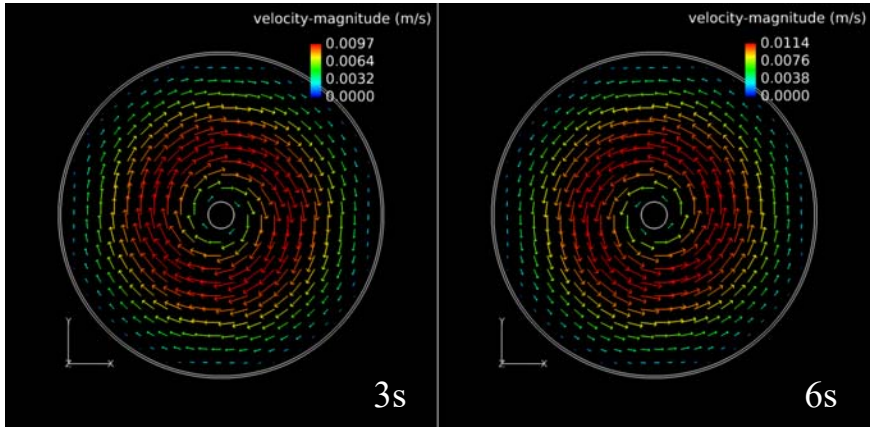
(a)



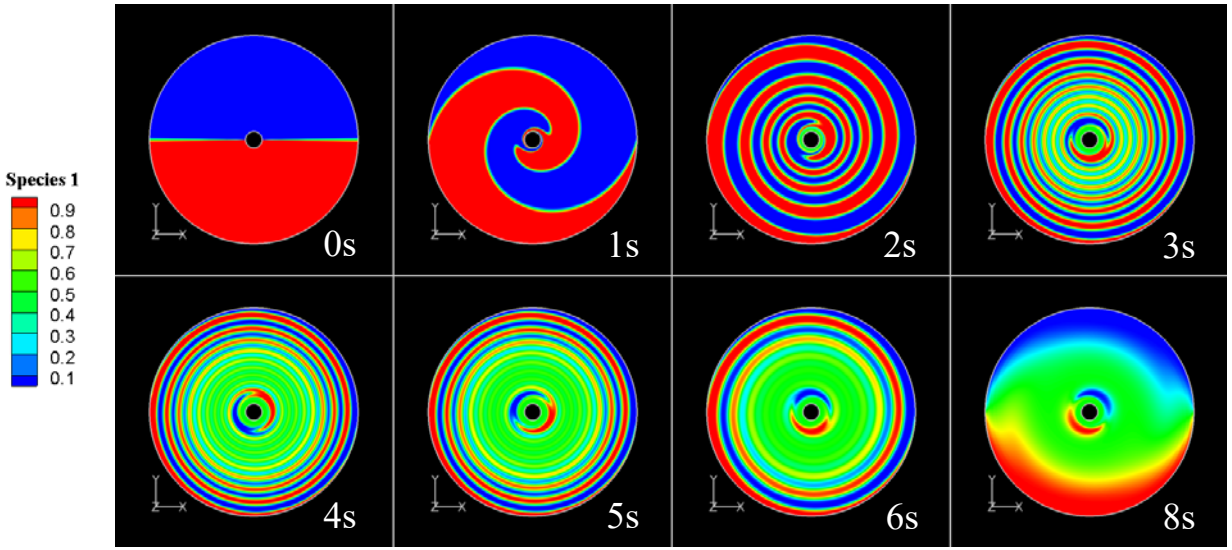
(b)

(a): Time evolution of the electric current and voltage on the working electrode. Concentric cylinder, $T=t_{max}$=8s and B=1.75T.
(b): Time evolution of maximum velocity magnitude in the whole domain. Concentric cylinder, $T=t_{max}$=8s and B=1.75T.

Results (4)
Concentric cylinder, configuration (a)

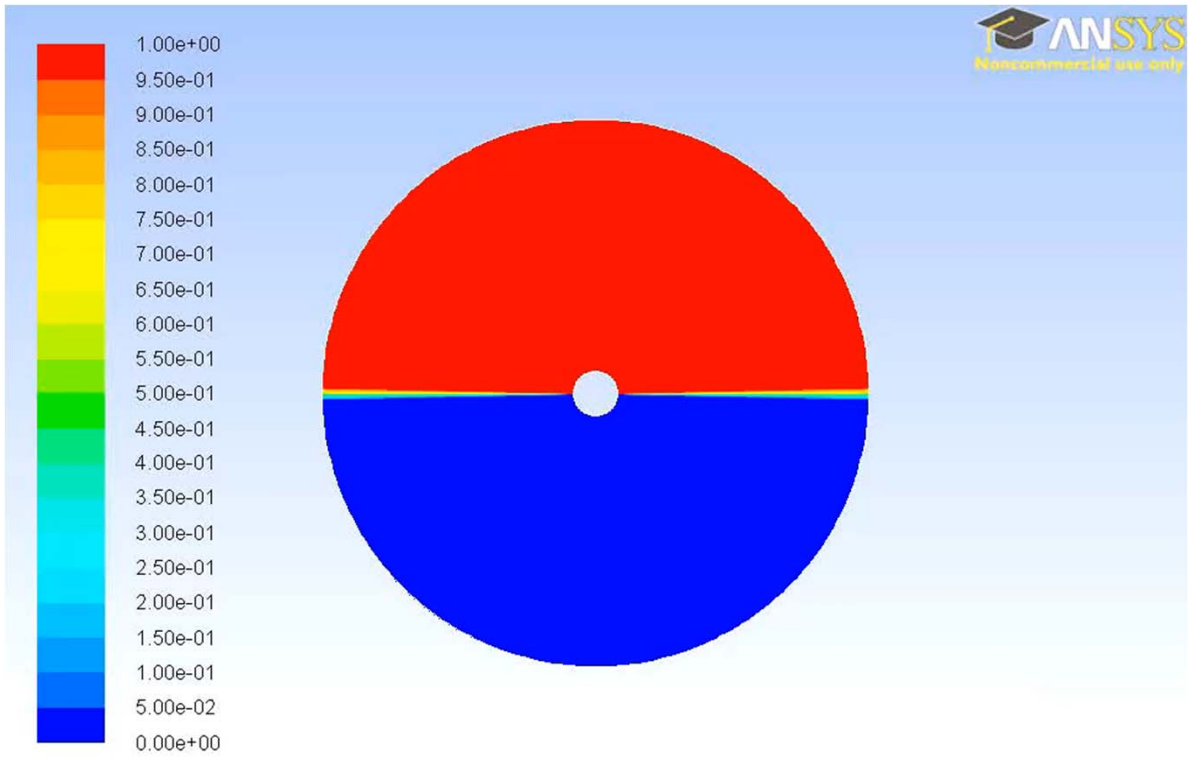


Velocity vectors at t=3s and 6s. Concentric cylinder $T=t_{max}$=8s and B=1.75T.

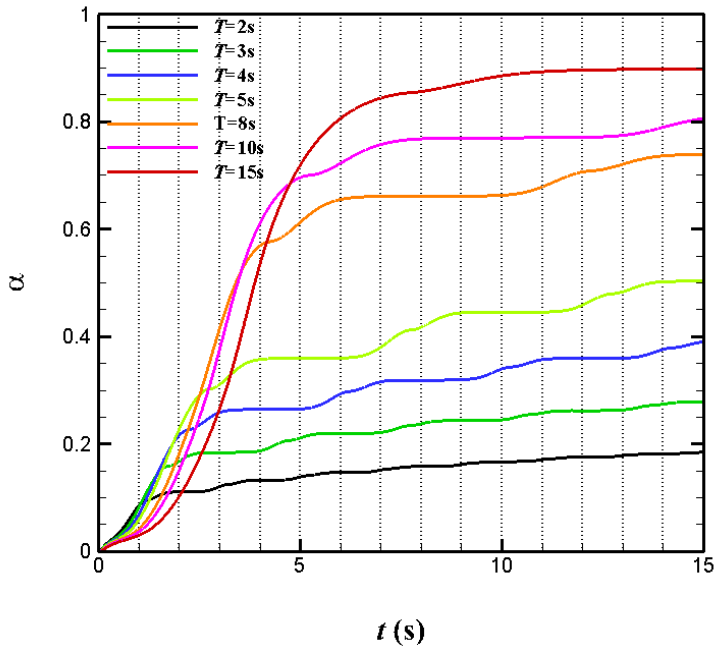


Time evolution of species mass fraction at t=0s, 1s, 2s, 3s, 4s, 5s, 6s and 8s. Concentric cylinder, $T=t_{max}$=8s and B=1.75T.

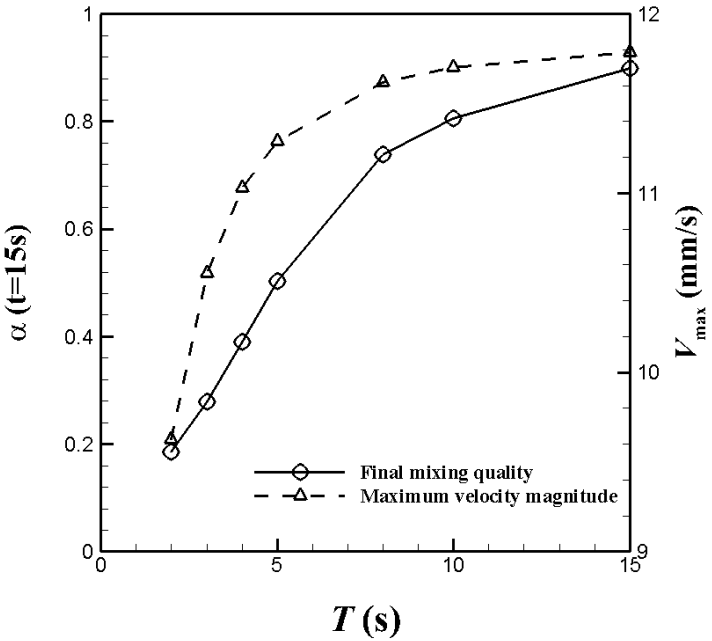
Concentric cylinder, T=8s, B=1.75T



Results (5)
Concentric cylinder, configuration (a)



(a)

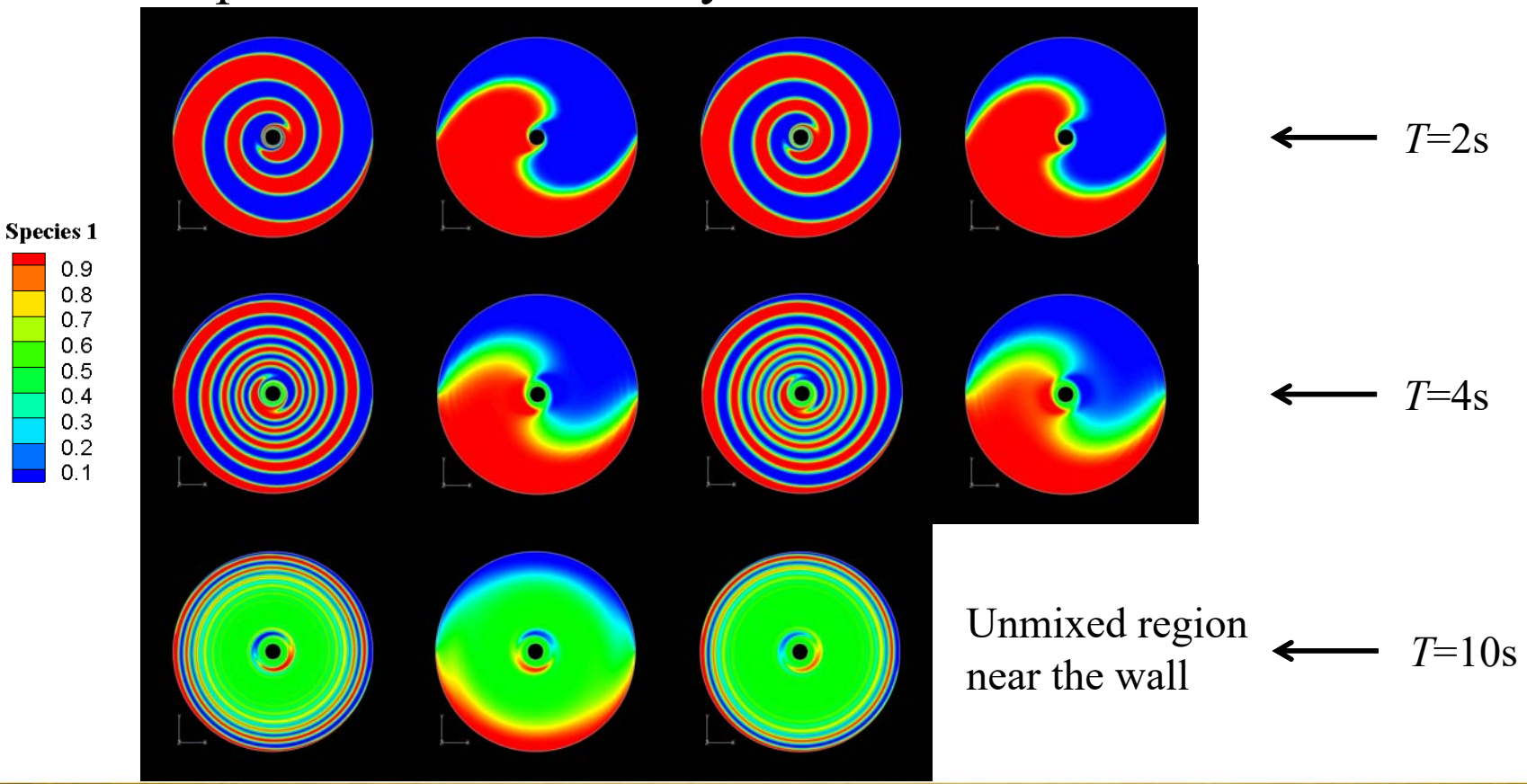


(b)

(a): Time evolution of mixing qualities with different time period *T*.
(b): Final mixing quality (solid line with circle symbol) and the maximum velocity magnitude (dashed line with delta symbol) as a function of time period *T*. Concentric cylinder, t_{max}=15s and *B*=1.75T.

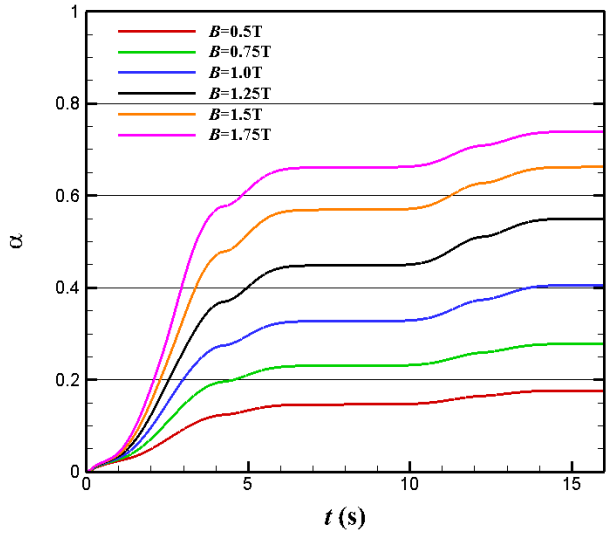
Results (6)
Concentric cylinder, configuration (a)

- Time evolution of species mass fraction of T=2s, 4s and 10s. Snapshots are taken every T/2.

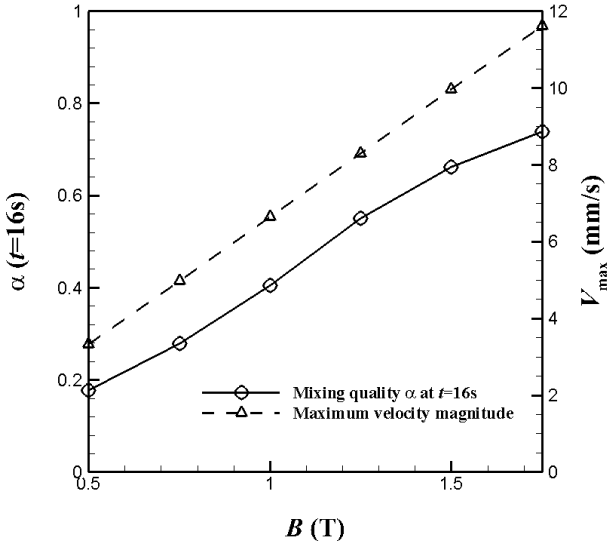


Results (7)
Concentric cylinder, configuration (a)

- The effect of magnetic field intensity *B*. Concentric cylinder model, *T*=8s, *t*=16s.



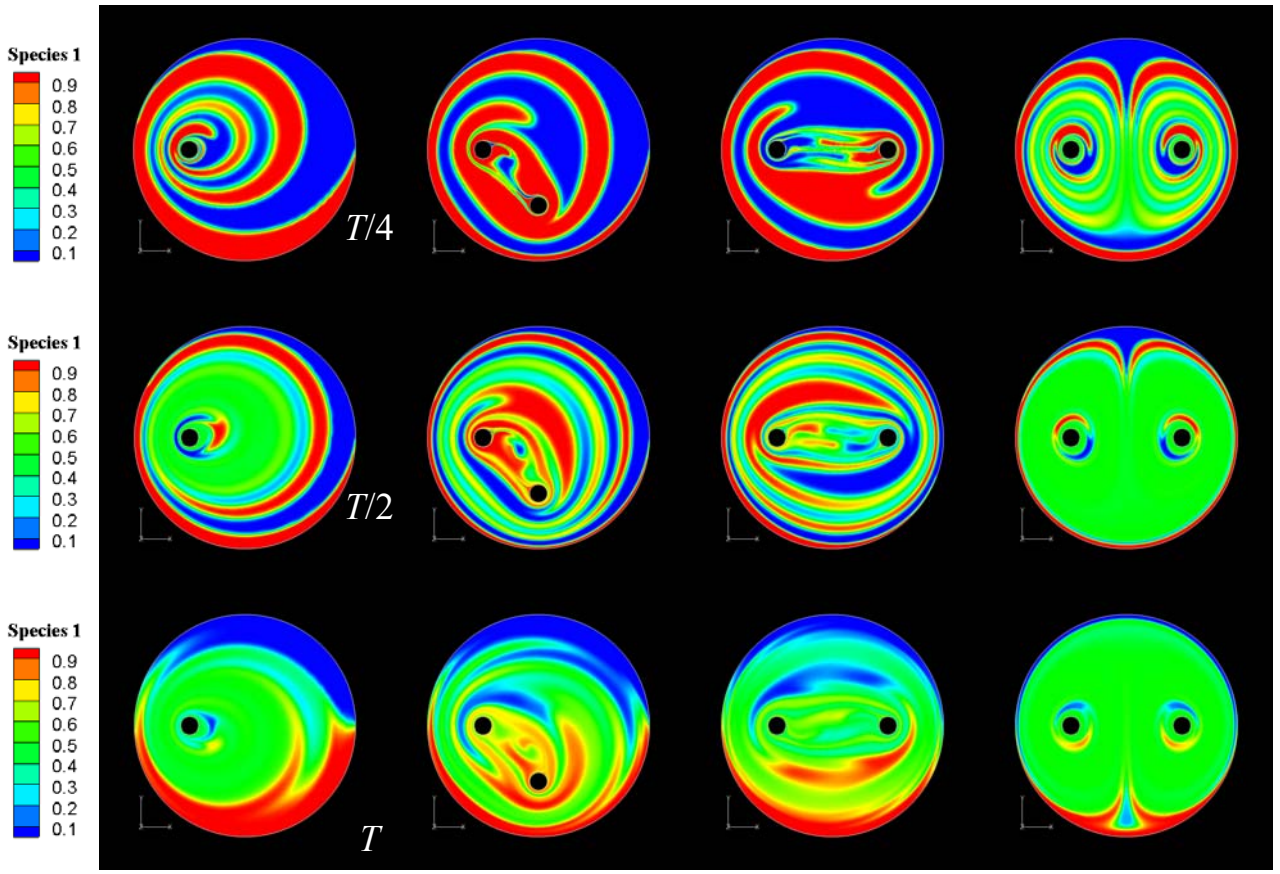
(a)



(b)

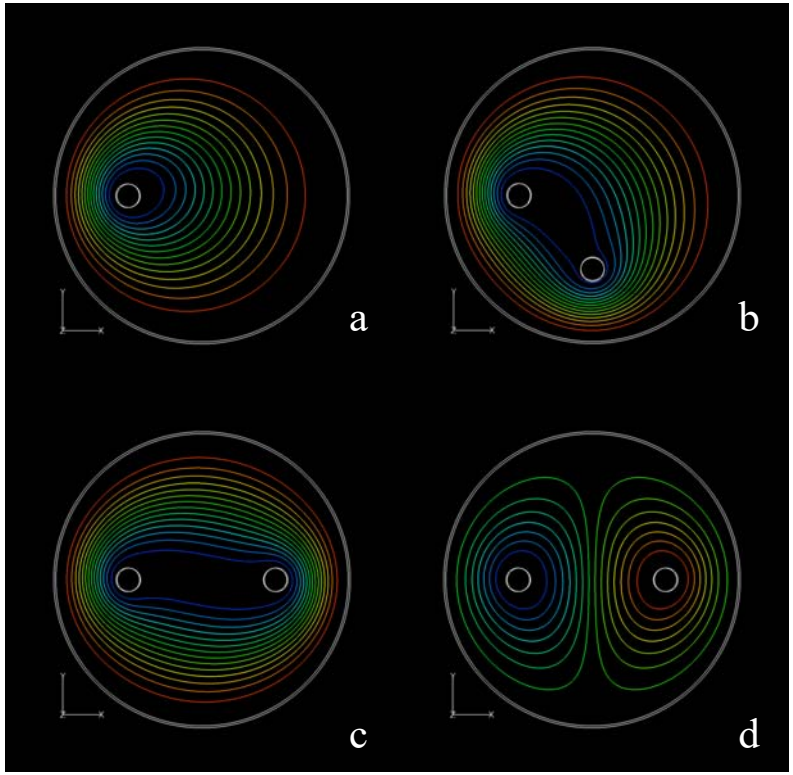
- (a): Mixing quality as a function of time *t* with different magnetic field intensity *B*.
- (b): Final mixing quality and maximum velocity magnitude as a function of magnetic field intensity *B*. Concentric cylinder, *T*=8s and t_{max}=16s.

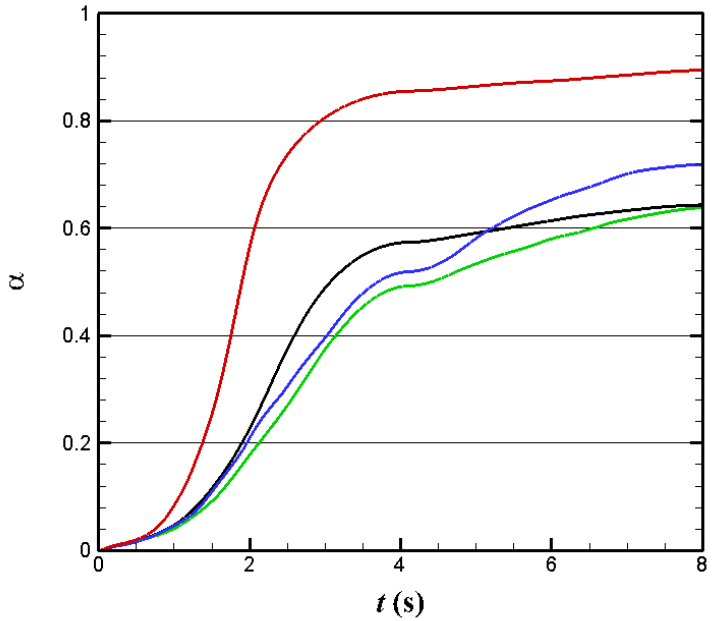
Results (8)
Configurations (b)-(d)



Species mass fraction contours for (I): eccentric cylinder, (II): two electrodes at 6 and 9 o'clock positions, (III): two electrodes at 3 and 9 o'clock positions with same signs for potential boundary conditions and (IV): two electrodes at 3 and 9 o'clock positions with opposite signs for potential boundary conditions. $t=T/4$ (a), $T/2$ (b) and T (c). $T=t_{max}=8$s and $B=1.75$T.

Results (9)
Configuration (b)-(d)

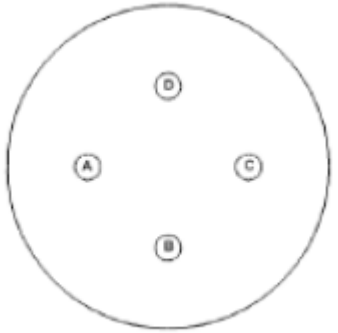




Left figure: Stream function at t=2s. (a): eccentric cylinder, (b): two electrodes at 6 and 9 o'clock positions with identical potential boundary conditions, (c): two electrodes at 3 and 9 o'clock positions with identical potential boundary conditions and (d): two electrodes at 3 and 9 o'clock positions with potential boundary conditions with the sign reversed. $T=t_{max}$=8s and B=1.75T.

Right figure: Mixing quality α as a function of time t. Black lines corresponds to figure a on the left, Green->b, Blue->c and Red->d.

Results (10)
Configuration (e)



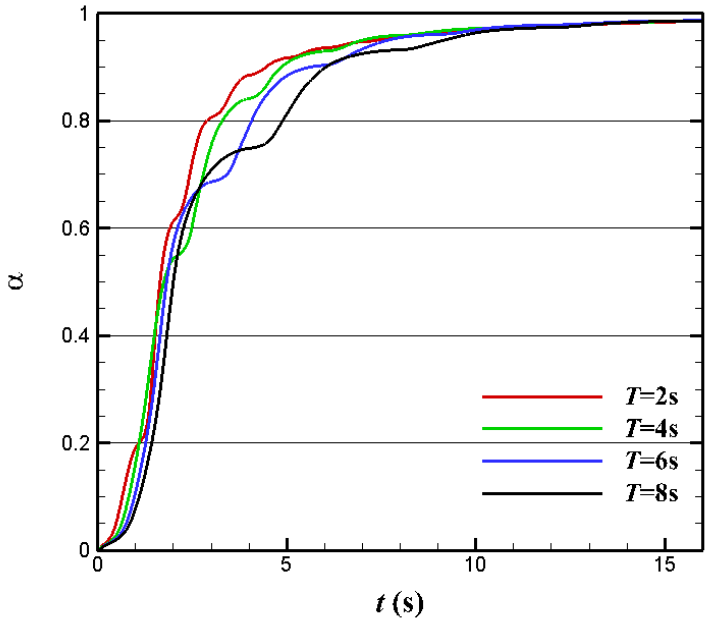
- Four working electrodes model.
- Alternative scheme to produce chaotic advection.
- Each pair of electrodes (AC and BD) generates a counter-rotating flow and the two pairs alternatively switch on and off.
- For the first half period,

$$\phi_A = \phi_0 \sin(2\pi t / T), \quad \phi_C = -\phi_0 \sin(2\pi t / T), \quad \phi_B = \phi_D = 0 \quad (kT \le t \le kT + T/2)$$

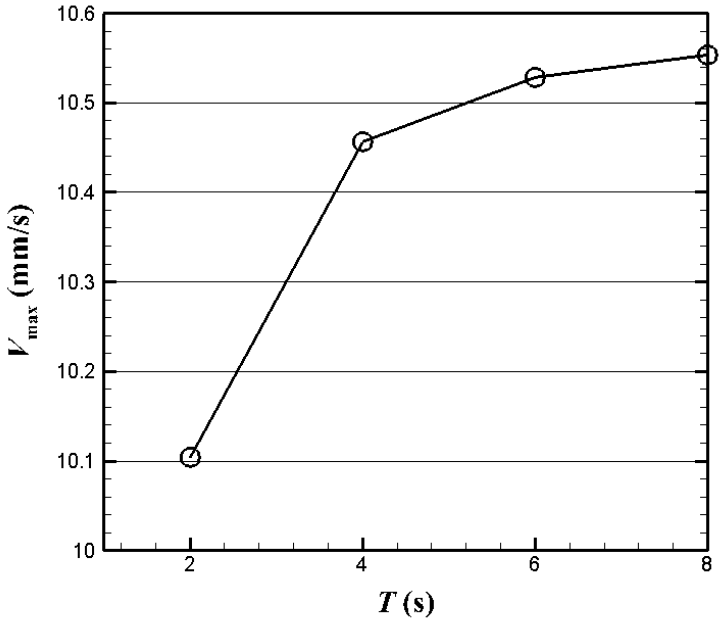
- For the next half period,

$$\phi_A = \phi_C = 0, \quad \phi_B = \phi_0 \sin(2\pi t / T), \quad \phi_D = -\phi_0 \sin(2\pi t / T) \quad (kT + T/2 \le t \le (k+1)T)$$

Results (11)
Configuration (e), *B*=1.75T



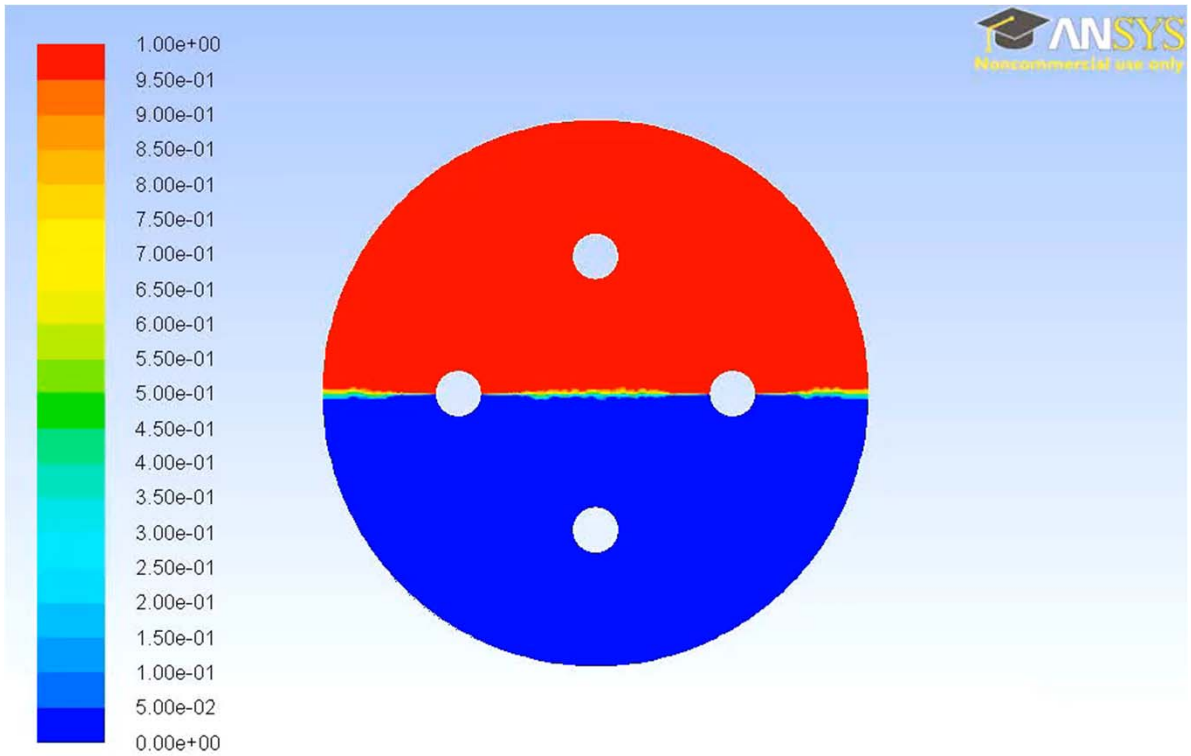
(a)



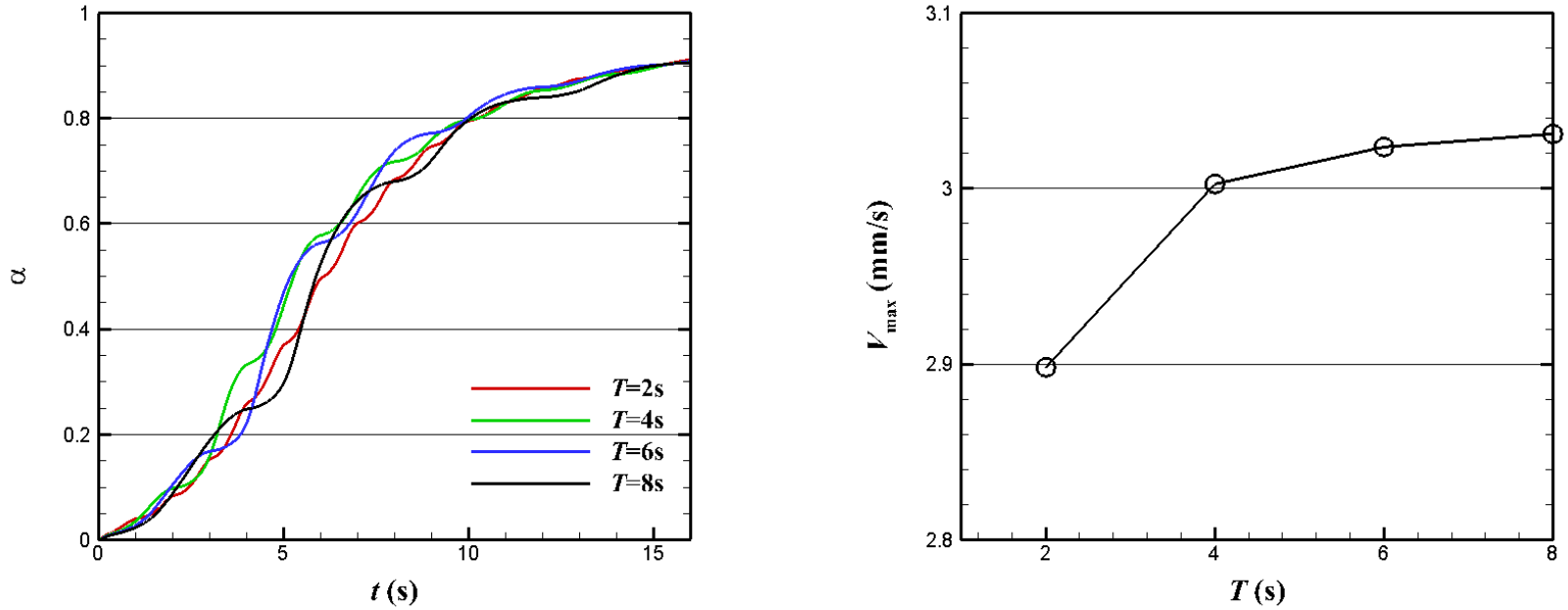
(b)

(a): Mixing quality vs. time for different time periods *T*. Color coding: Red: *T*=2s, Green: *T*=4s, Blue: *T*=6s and Black: *T*=8s. (b): Maximum velocity magnitude in the computational domain vs. time periods *T*. t_{max} = 16s and *B*=1.75T.

T=8s, B=1.75T


1.00e+00
9.50e-01
9.00e-01
8.50e-01
8.00e-01
7.50e-01
7.00e-01
6.50e-01
6.00e-01
5.50e-01
5.00e-01
4.50e-01
4.00e-01
3.50e-01
3.00e-01
2.50e-01
2.00e-01
1.50e-01
1.00e-01
5.00e-02
0.00e+00
ANSYS
Noncommercial use only
Contours of Mass fraction of h2o1 (Time=4.0000e-02)
Jun 27, 2
ANSYS FLUENT 14.0 (2d, dp, pbns, spe, lam, trans

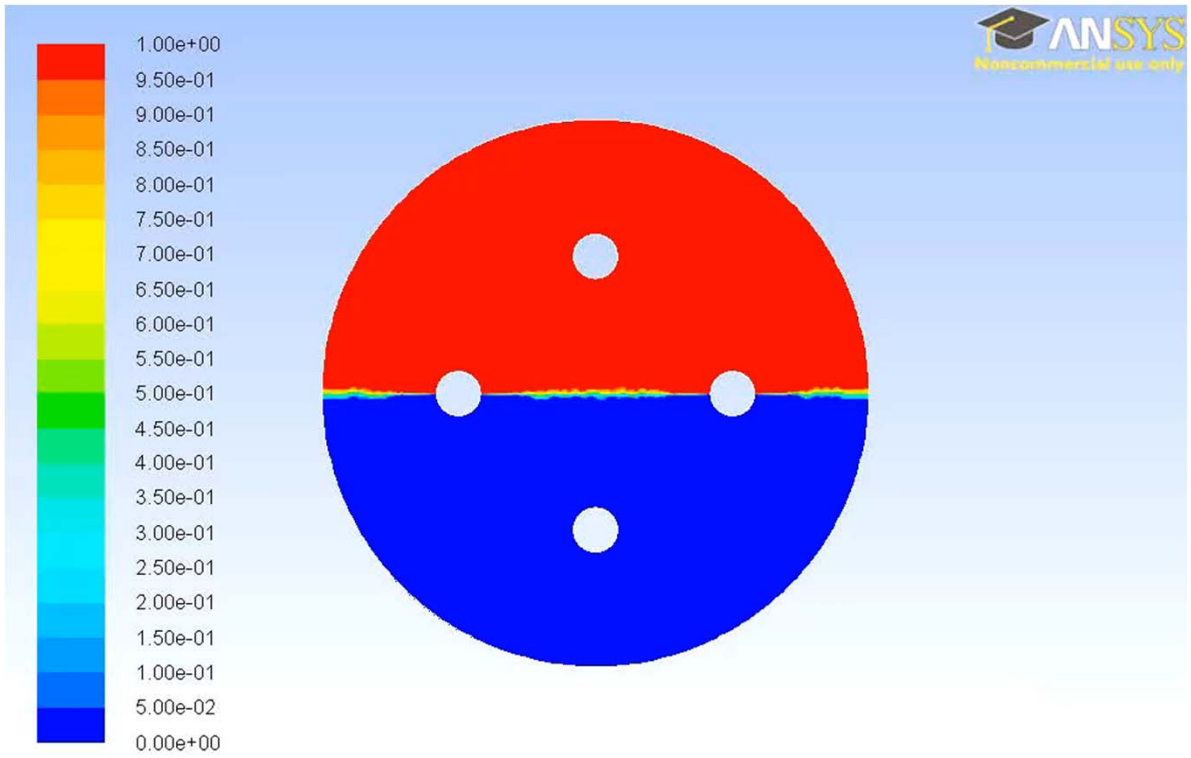
Results (12)
Configuration (e), *B*=0.5T



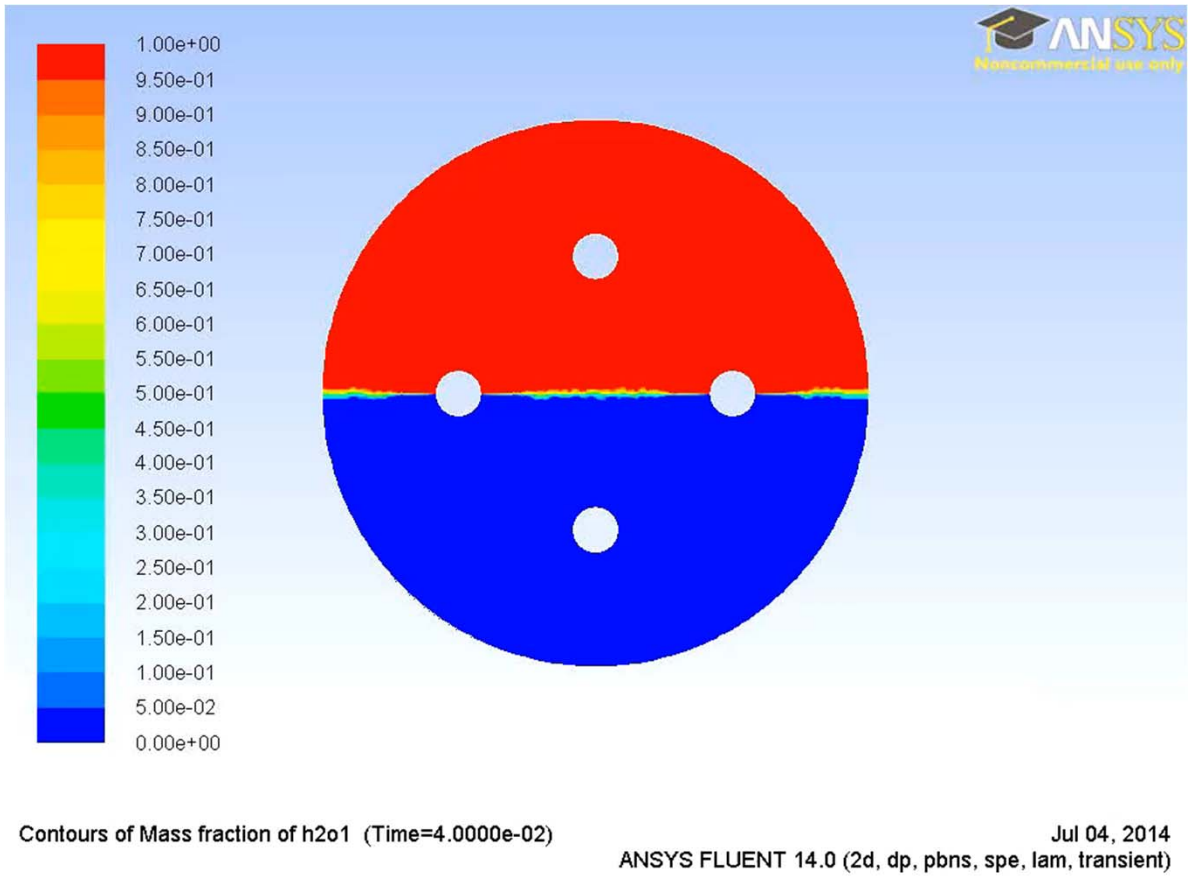
(a) (b)

(a): Mixing quality vs. time for different time periods *T* with *B*=0.5T and t_{max}=16s.
Color coding: Red line: *T*=2s, green line: *T*=4s, blue line: *T*=6s and black line: *T*=8s.
(b): Maximum velocity magnitudes vs. different time periods *T*.

T=2s, B=0.5T


1.00e+00
9.50e-01
9.00e-01
8.50e-01
8.00e-01
7.50e-01
7.00e-01
6.50e-01
6.00e-01
5.50e-01
5.00e-01
4.50e-01
4.00e-01
3.50e-01
3.00e-01
2.50e-01
2.00e-01
1.50e-01
1.00e-01
5.00e-02
0.00e+00
ANSYS
Noncommercial use only
Contours of Mass fraction of h2o1 (Time=4.0000e-02)
Jul 11, 2
ANSYS FLUENT 14.0 (2d, dp, pbns, spe, lam, trans

T=4s, B=0.5T


1.00e+00
9.50e-01
9.00e-01
8.50e-01
8.00e-01
7.50e-01
7.00e-01
6.50e-01
6.00e-01
5.50e-01
5.00e-01
4.50e-01
4.00e-01
3.50e-01
3.00e-01
2.50e-01
2.00e-01
1.50e-01
1.00e-01
5.00e-02
0.00e+00
ANSYS
Noncommercial use only
Contours of Mass fraction of h2o1 (Time=4.0000e-02)
Jul 04, 2014
ANSYS FLUENT 14.0 (2d, dp, pbns, spe, lam, transient)

Conclusion

- A certain level of mixing can be achieved by the simple use of sinusoidal potential boundary conditions on one pair of electrodes.
- The time period has a strong influence on the mixing quality for the concentric cylinder model because of long time period allows the interface to be stretched and folded much more. Obviously, higher magnetic field intensity provides a higher velocity magnitude and therefore enhance mixing.
- By introducing more than one flow structure, more complex chaotic fluidic flows can be obtained which strongly enhance mixing even under a small magnetic field intensity.

Future work

- Focus on 3D simulations with detailed analysis of chaotic advection including Poincare map, material line/blob stretching experiment, Lyaponov exponent, and other similar analyses.

Acknowledgement

- NSF funding, Grant Award Number CBET-1336722.

- Assistantship from MAE Department at Missouri University of Science and Technology.

Thank you!

- Any Questions?