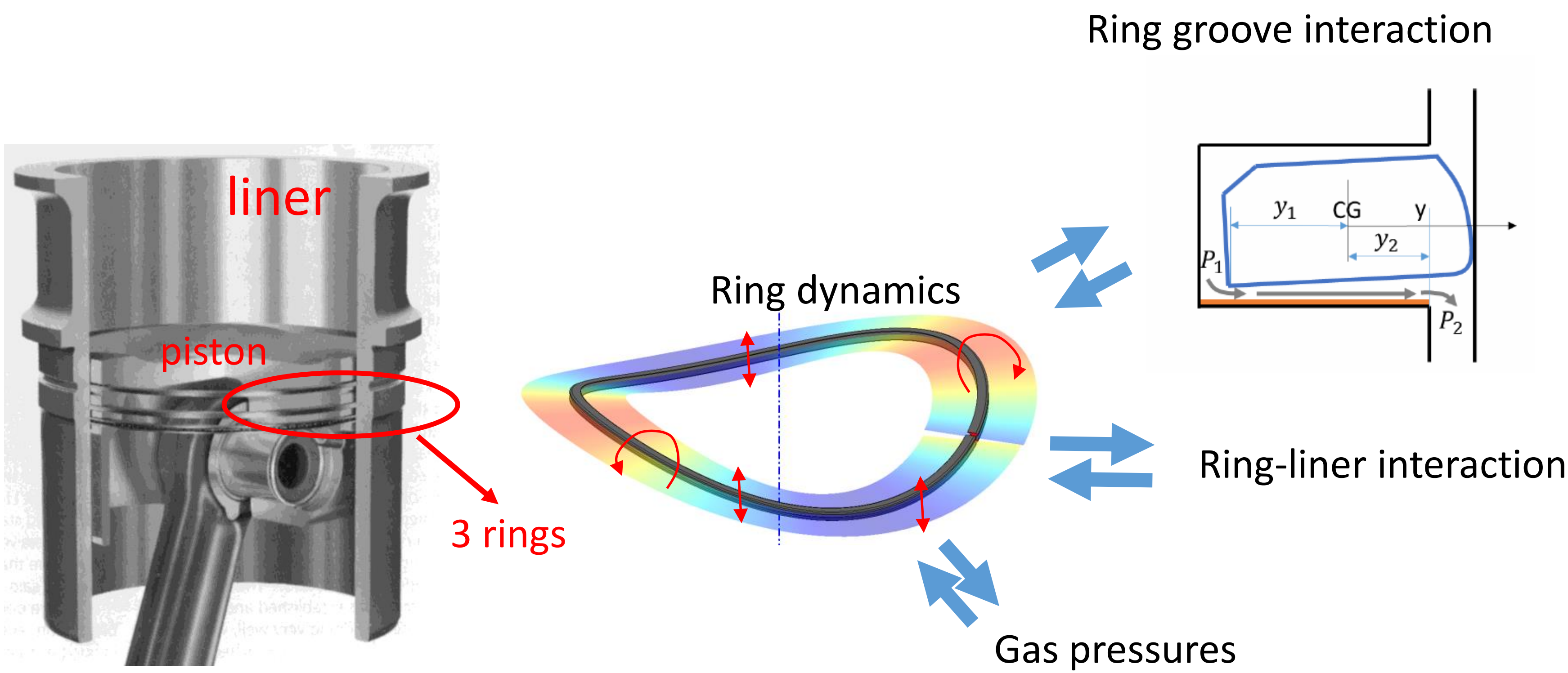
Massachusetts Institute of Technology

Developing a pumping model for piston ring-groove oil/air transportation in IC engines

Wang Zhang

May 16, 2018

Background



liner
piston
3 rings
Ring dynamics
Ring groove interaction
y_1
CG
y
y_2
P_1
P_2
Ring-liner interaction
Gas pressures

Motivation and requirement for “pumping” model

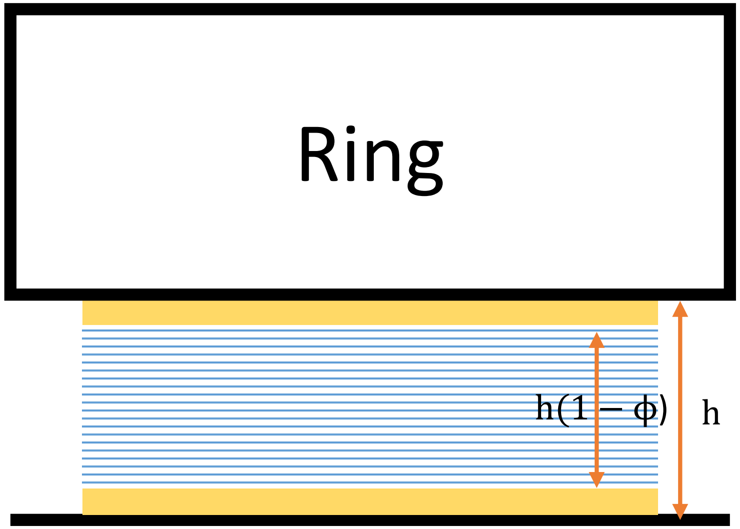
- Describe the oil/gas transportation

----acceptable accuracy

- Eventually working as a sub-model for 3D ring dynamics model

----simplicity and robustness

Pumping model assumption



Piston groove

h is the clearance (which is an input right now)

ϕ is the volume ratio of the oil

Assumption:

- 2D fluid
- Qualified for Reynolds equation like simplification of NS equation

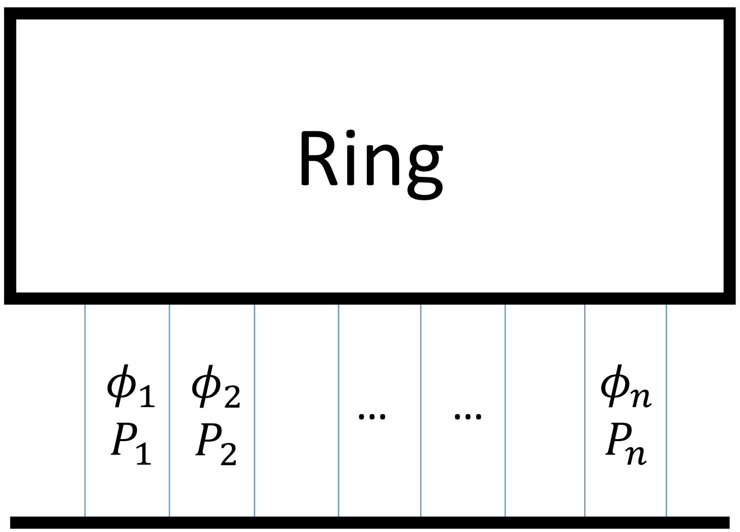
$$\frac{\partial \mathrm{P}}{\partial \mathrm{x}} - \mu \frac{\partial V_x}{\partial z^2} = 0$$

- Oil: incompressible
  Air: compressible($\rho \propto \mathrm{P}$)
- Oil are attached on both side symmetrically the mid tunnel is for air
- Piston is static, ring only has velocity in z axle.
- Boundary conditions:

BC1: $@\mathrm{y} = 0, \mathrm{V_x} = 0$	Non-slip wall
BC2: $@\mathrm{z} = \frac{\mathrm{h}}{2}, \frac{\partial \mathrm{V_x}}{\partial \mathrm{z}} = 0$	Symmetry
BC3: $@\mathrm{z} = \frac{\phi \mathrm{h}}{2}, \mathrm{V_{xo}} = V_{xa}$	Velocity continuity on interface
BC4: $@\mathrm{z} = \frac{\phi \mathrm{h}}{2}, \frac{\mu_o \partial V_{xo}}{\partial z} = \frac{\mu_a \partial V_{xa}}{\partial z}$	Shear stress continuity on interface

- Mass conservation

Pumping model assumption



$$\frac{\partial(\phi h)}{\partial t} = \frac{\partial}{\partial x}[\frac{1}{24\mu_l}\phi^2(3-\phi)h^3\frac{\partial P}{\partial x}]$$

Oil mass conservation

$$\frac{\partial[(1-\phi)hP]}{\partial t} = \frac{\partial}{\partial x}[\frac{1}{12\mu_a}P(1-\phi)^3h^3\frac{\partial P}{\partial x}]$$

Air mass conservation

h is the clearance (which is an input right now)

ϕ is the volume ratio of the oil

P is the local pressure

Choose normalization factors for equation

Oil mass conservation

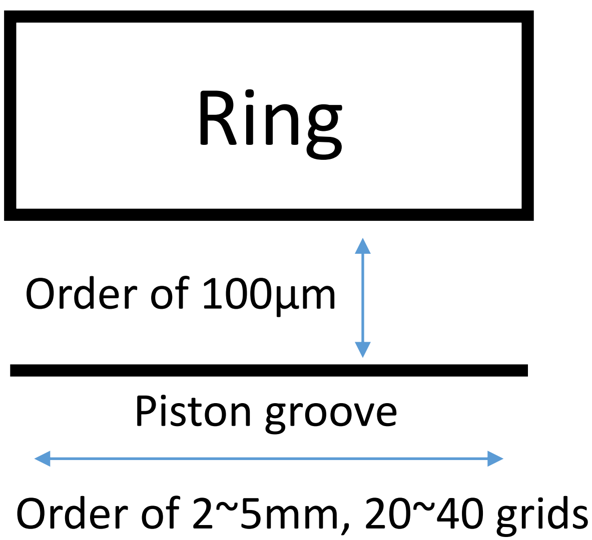
$$\frac{\partial(\phi h)}{\partial t} = \frac{\partial}{\partial x}[\frac{1}{24\mu_l}\phi^2(3-\phi)h^3\frac{\partial P}{\partial x}]$$

$$\frac{\partial(\phi h^*)}{\partial t^*} = \frac{h_{ref}^2 t_{ref} P_{ref}}{24\mu_l x_{ref}^2}\frac{\partial}{\partial x^*}[\phi^2(3-\phi)h^{*3}\frac{\partial P^*}{\partial x^*}]$$

Air mass conservation

$$\frac{\partial[(1-\phi)hP]}{\partial t} = \frac{\partial}{\partial x}[\frac{1}{12\mu_a}P(1-\phi)^3 h^3\frac{\partial P}{\partial x}]$$

$$\frac{\partial[(1-\phi)h^* P^*]}{\partial t^*} = \frac{P_{ref} h_{ref}^2 t_{ref}}{12\mu_a x_{ref}^2}\frac{\partial}{\partial x^*}\left[P^*(1-\phi)^3 h^{*3}\frac{\partial P^*}{\partial x^*}\right]$$



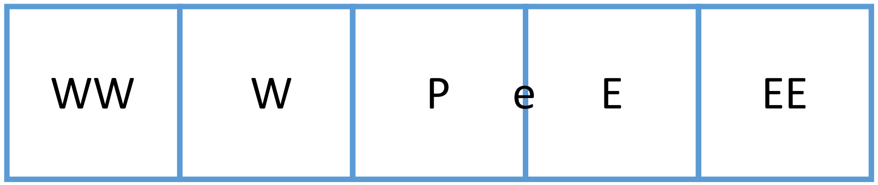
$$\mu_a \sim 3e-5\ Pa \cdot s$$
$$\mu_l \sim 3e-3\ Pa \cdot s$$
$$dt \sim 2e-5s$$
$$(\ \delta crankangle = 0.1,$$
$$\text{engine speed} \sim 3000\ \text{rev/min})$$

Normalization factors:

$$x_{ref} = 1e-4$$
$$h_{ref} = 1e-4$$
$$P_{ref} = 1e5$$
$$t_{ref} = 1e-6$$

Jacobian matrix:
Condition number~ 10~200
Determinant ~ 0.1~10

Choose FV method scheme



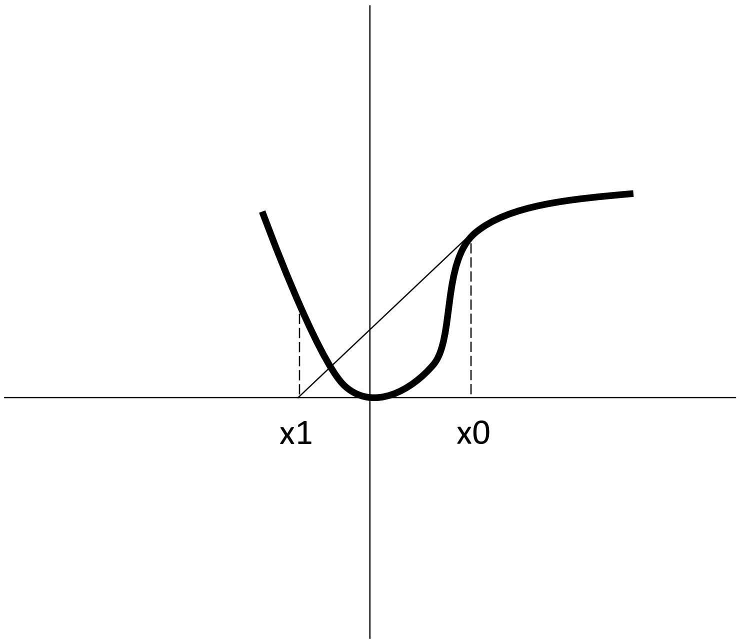
$$\frac{\partial(\phi h)}{\partial t} = \frac{\partial}{\partial x}[\frac{1}{24\mu_l}\underbrace{\phi^2(3-\phi)h^3}\frac{\partial P}{\partial x}]$$

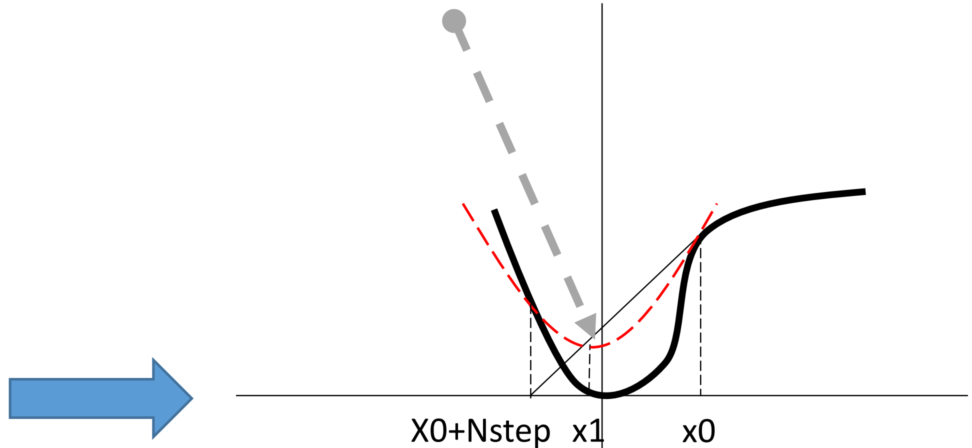
$$\frac{\partial[(1-\phi)hP]}{\partial t} = \frac{\partial}{\partial x}[\frac{1}{12\mu_a}\underbrace{P(1-\phi)^3h^3}\frac{\partial P}{\partial x}]$$

Diffusion coefficient on cell boundary

Methods	Convergence
Linear + explicit	Not convergent
Linear + implicit	Not convergent
Upwind(direction defined by Pressure)+explicit	Not convergent
Upwind + implicit	Finally worked…
Upwind + Crank-Nicholson	Similar to implicit
Upwind QUICK + implicit	Didn't try, for the Jacobian is too long…
Upwind QUICK + deferred correction	Convergent but oscillating
Solve diffusion coefficient explicitly, then correct it by solving derivative terms implicitly	I thought it's a good idea, but not working…

Line search for Newton iteration



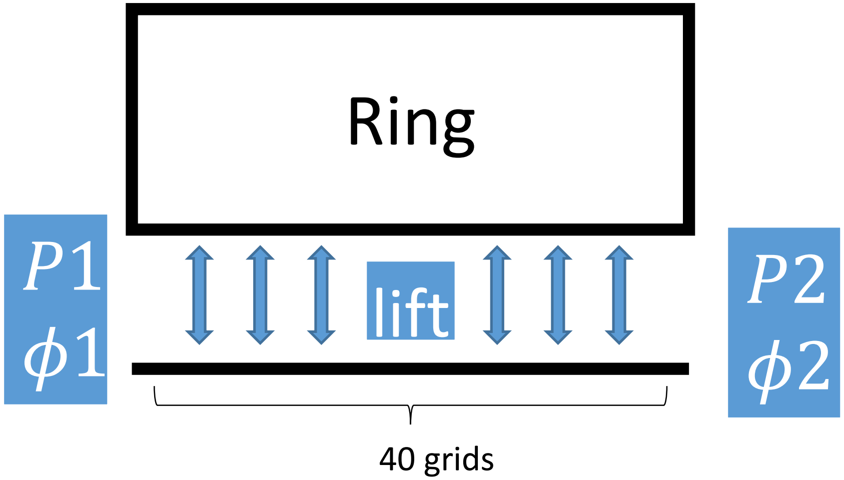



```
NLS_0=err_cal(pp);
g0=0.5*norm(NLS_0)^2;
NLS_1=err_cal(pp+step');
g1=0.5*norm(NLS_1)^2;
gg0=-2*g0;
a=(g1-g0-gg0);b=gg0;c=g0;
lambda=-b/2/a;
lambda=min(lambda,0.1);
lambda=max(lambda,0.5);
pp=pp+lambda*step';
```

Find minimum error position on the parabolic fitting

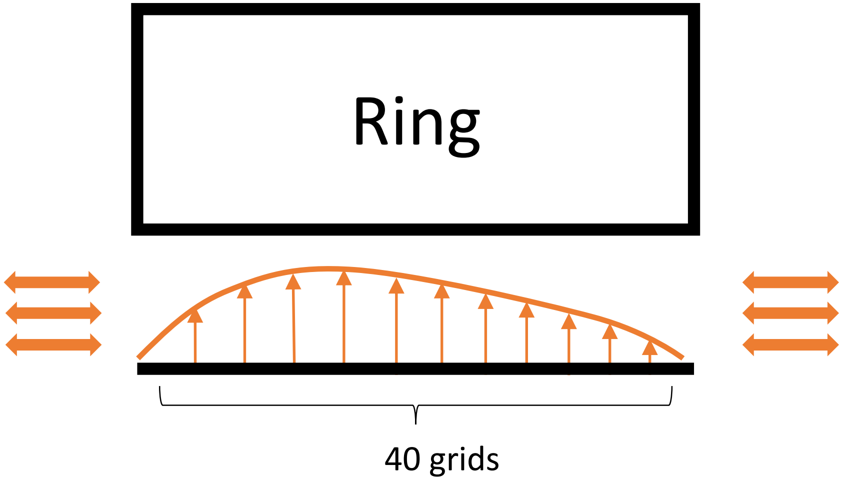
Model setup as a post-process

Input:



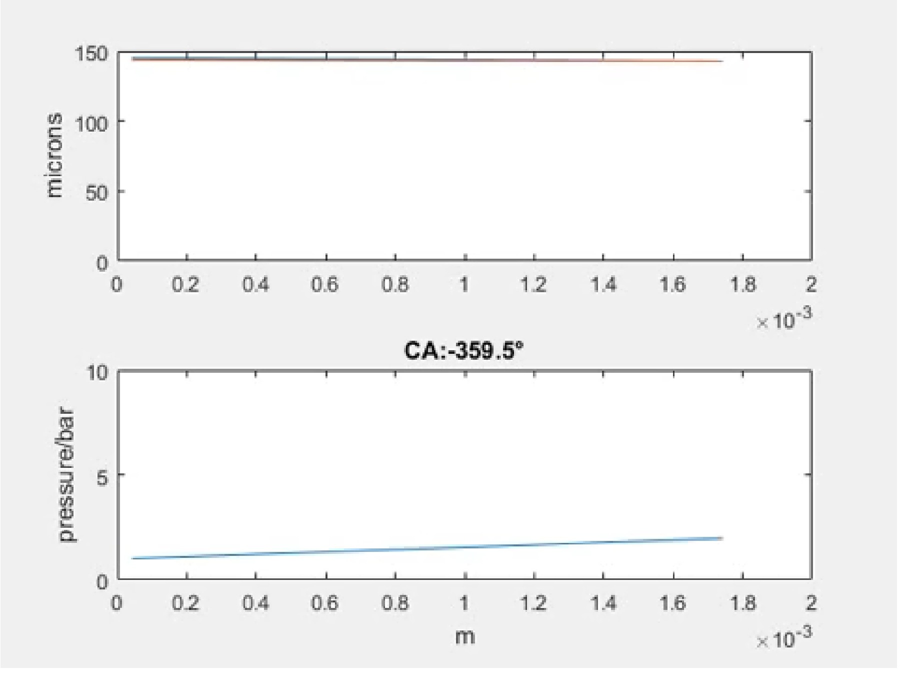
Output:

Pressure distribution
Oil film thickness
Oil flow rate

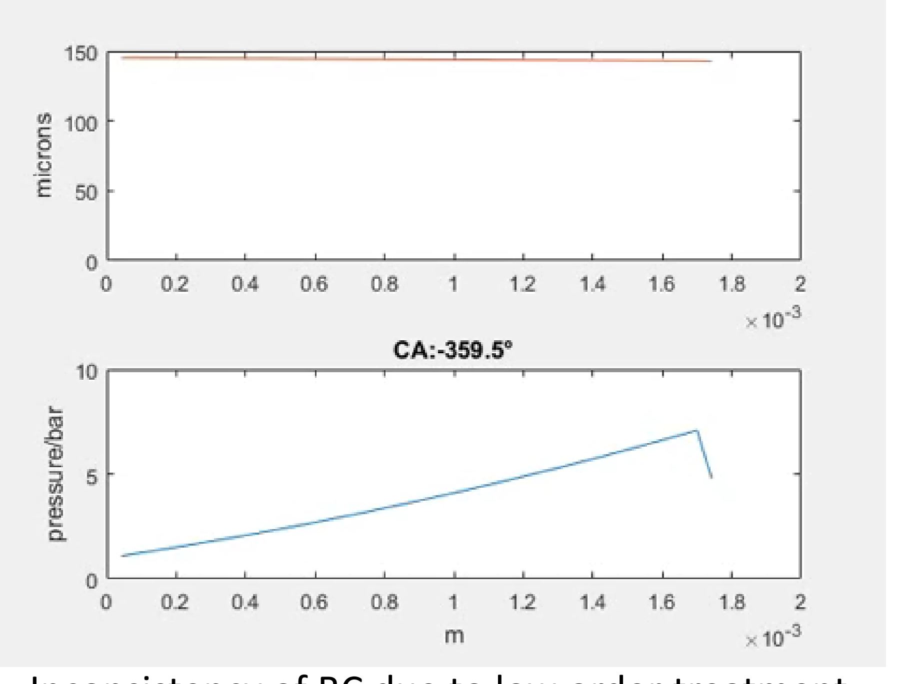


Preliminary results

Upwind



Upwind QUICK deferred



Inconsistency of BC due to low order treatment

Oil flow rate(mm^2/s)

	Upwind		Upwind+deferred QUICK	
Boundary Conditions	ID (left boundary)	OD (right boundary)	ID	OD
P1=1Bar P2=1.5Bar	103.4052	103.4044	0.051062	-0.87704
P1=1Bar P2=2Bar	210.6707	210.668	0.044485	-1.0096
P1=1Bar P2=2.5Bar	318.0667	318.0621	0.065577	-0.97826

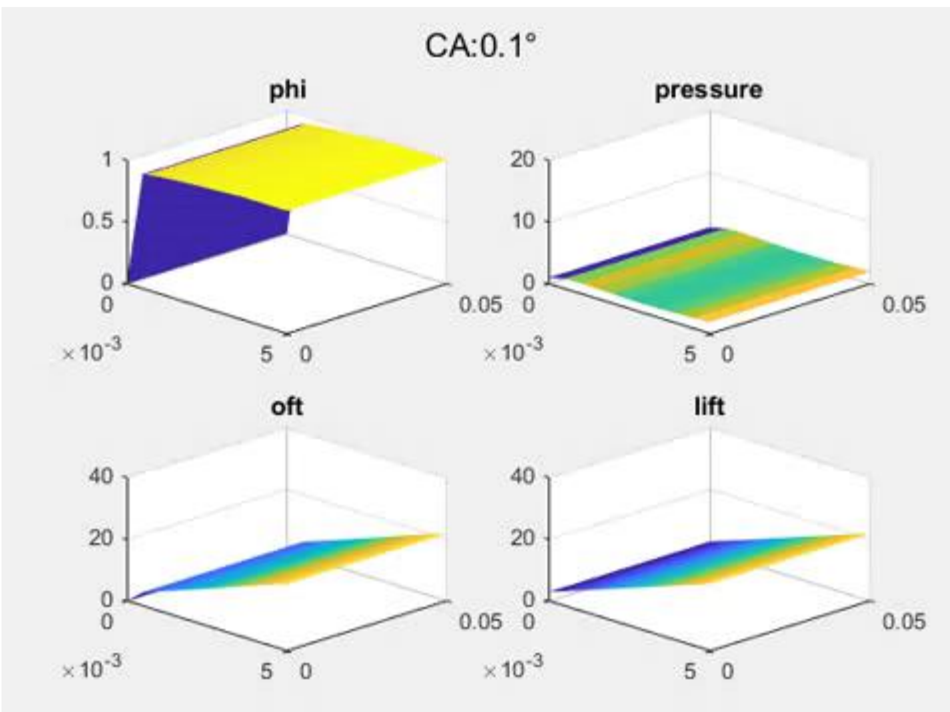
Flow rate $\propto \Delta P$

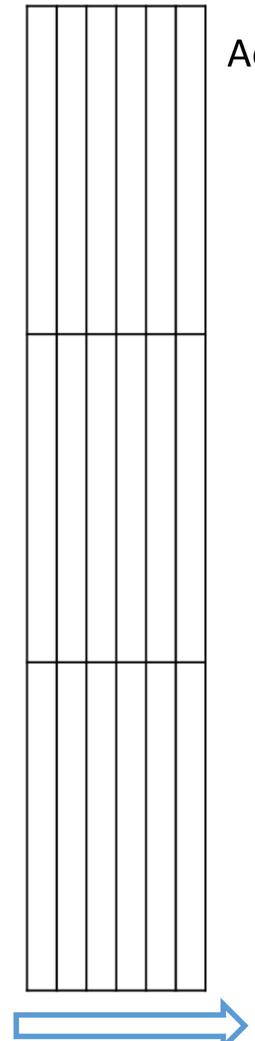
Unacceptable error
Due to boundary treatment

2D model

$$\frac{\partial(\phi h)}{\partial t} = \frac{\partial}{\partial x}\left[\frac{1}{24\mu_l}\phi^2(3-\phi)h^3\frac{\partial P}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{1}{24\mu_l}\phi^2(3-\phi)h^3\frac{\partial P}{\partial y}\right]$$

$$\frac{\partial[(1-\phi)hP]}{\partial t} = \frac{\partial}{\partial x}\left[\frac{1}{12\mu_a}P(1-\phi)^3h^3\frac{\partial P}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{1}{12\mu_a}P(1-\phi)^3h^3\frac{\partial P}{\partial y}\right]$$





Add one more dimension y

Assume periodic BC in y direction

Original 1D direction

Discussions for 2D model

- CFL condition for implicit scheme

$\delta\ crank\ angle$ (°CA)	$\delta t(\mathrm{s})$	Maximum cells without divergence	$\delta x(\mathrm{m})$	$\frac{\delta t}{\delta x}(\mathrm{s/m})$
0.1	1.6667e-05	11	4.5455e-04	27.24
0.05	8.3335e-06	16	3.1250e-04	37.50
0.01	1.6667e-06	29	1.7241e-04	103.44

- Normalization factors

Thanks!