Investigation of Oil Transport on IC Engine Piston Land and Piston Ring Groove

Numerical Modeling and CFD Simulation

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2.29 Numerical Fluid Mechanics Final Presentation

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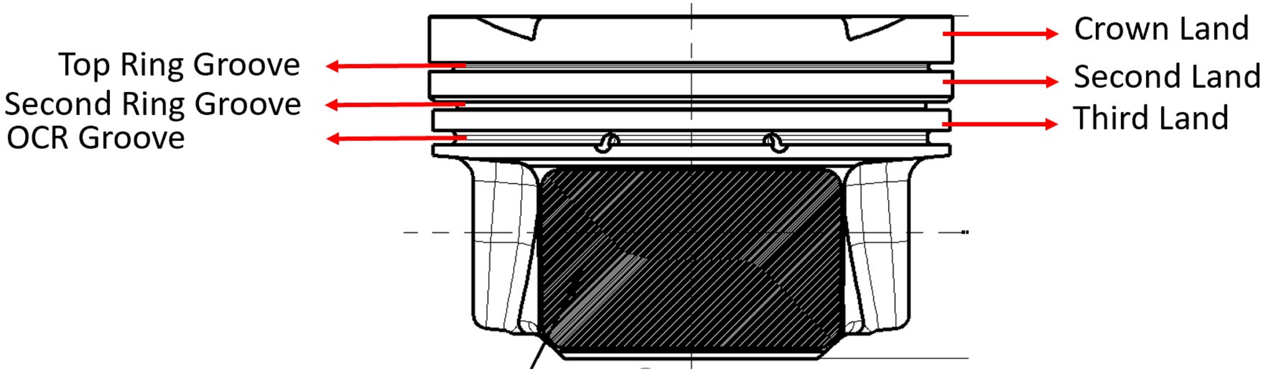
Background

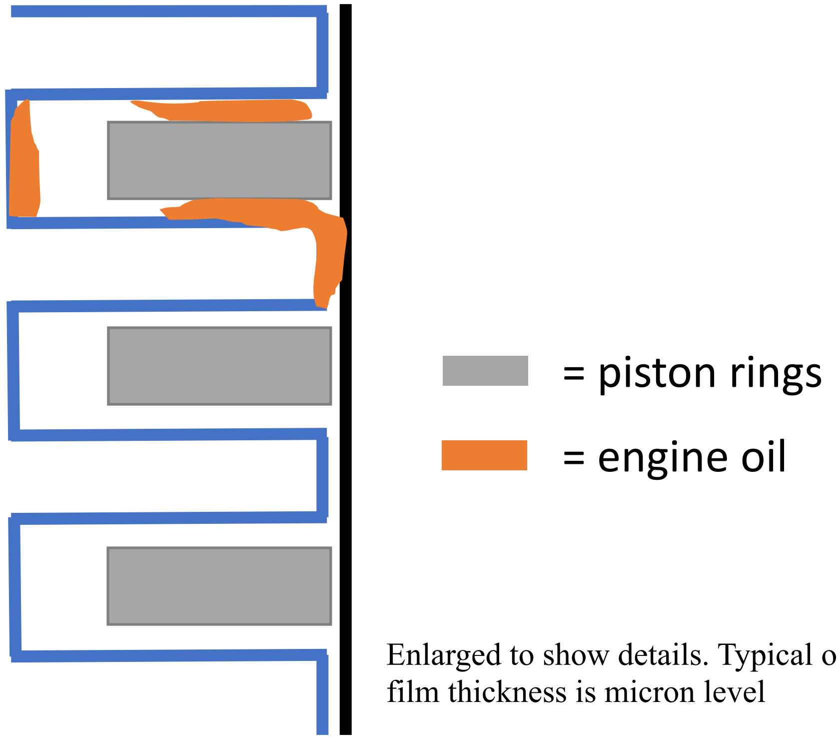
- One of the major source of particle emission from IC engine is lubricant oil consumption in piston ring pack system

- Oil transport in piston ring pack is heavily dependent on gas flow within the power cylinder system, which have the tendency to bring oil to the combustion chamber

- Other factors governing oil transport: piston ring dynamics, liner motion, body forces, engine load and RPM, etc.

- Necessary to develop an understanding of how oil is transported in the system to guide future designs





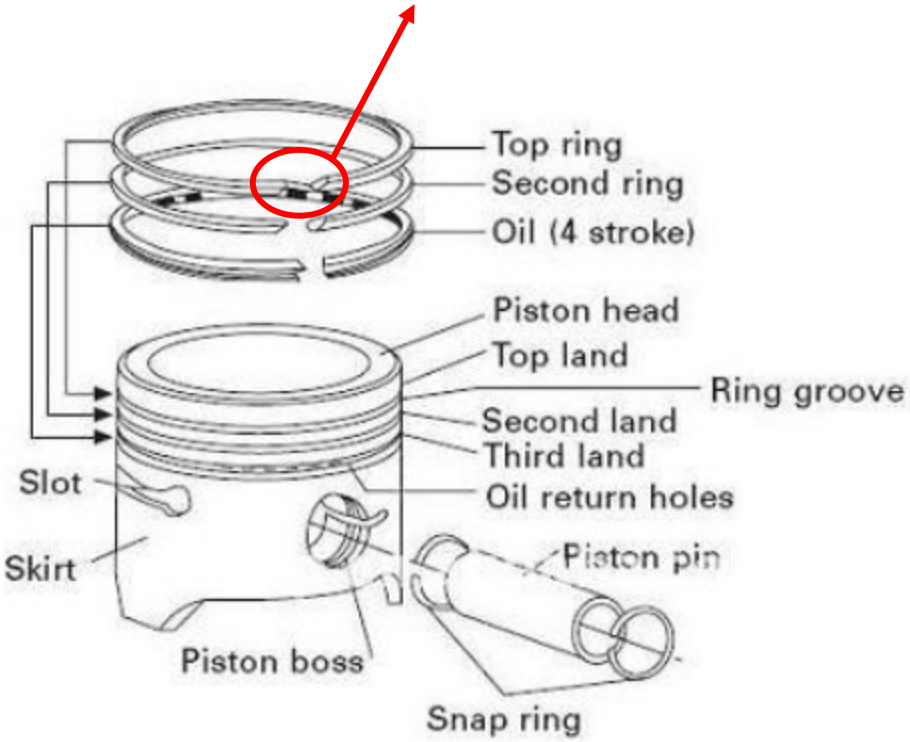
Enlarged to show details. Typical oil film thickness is micron level

Objective

The aims of this work are:

- Develop and implement a 2- dimensional numerical model to study the governing factors of oil transport in a region (partially adapted from previous work [McGrogan 2007] that studies carbon build-up on crown land)
- Perform multi-phase CFD simulation to show in details of the oil-gas interaction during peak cylinder pressure period
  - Comparisons between different schemes
- This work focuses solely on second land and second ring groove
- Compare results from numerical model and CFD
- Future works

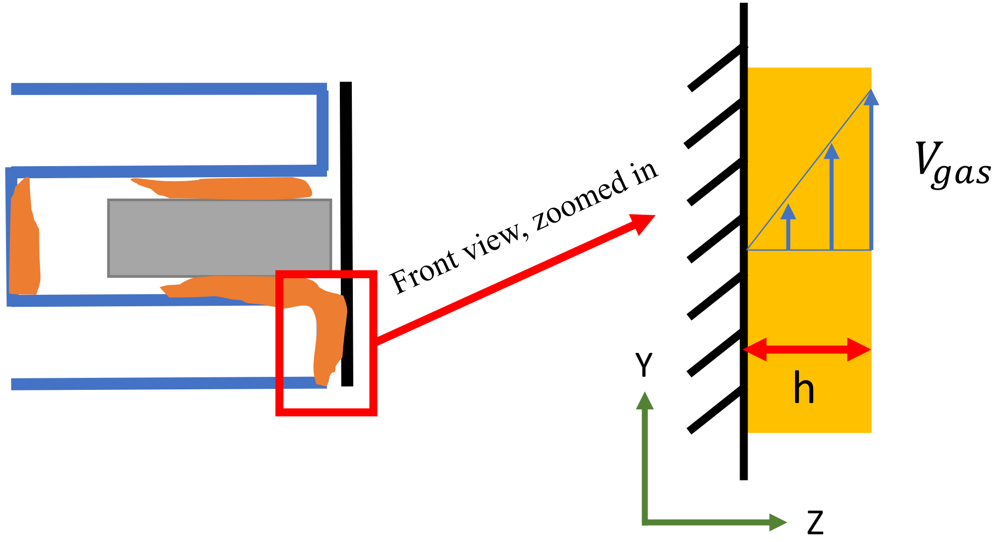
Each ring also has a gap that is open (important for boundary conditions)



Numerical Modeling – Governing Equations

Y-direction (axial direction)

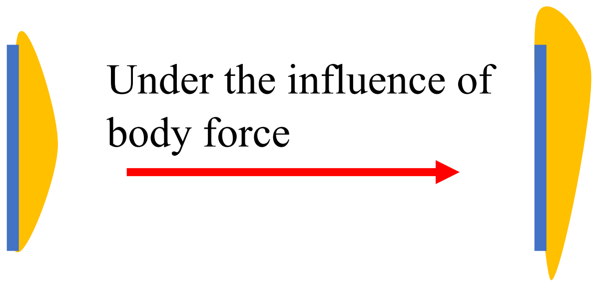
- Liquid oil motion governed by body force due to piston acceleration and axial gas velocity
- Assumptions:
  - Flow is locally fully developed and steady
  - Film thickness (h) << piston land height ($3e^{-6}$m/0.0048 m << 1)
  - Neglect variation of gas velocity in radial direction – oil velocity at gas-oil interface equals the gas velocity input at each point
  - No axial pressure gradient
- Model turns out to be a Couette flow with alternating body force



Governing equation can be derived as

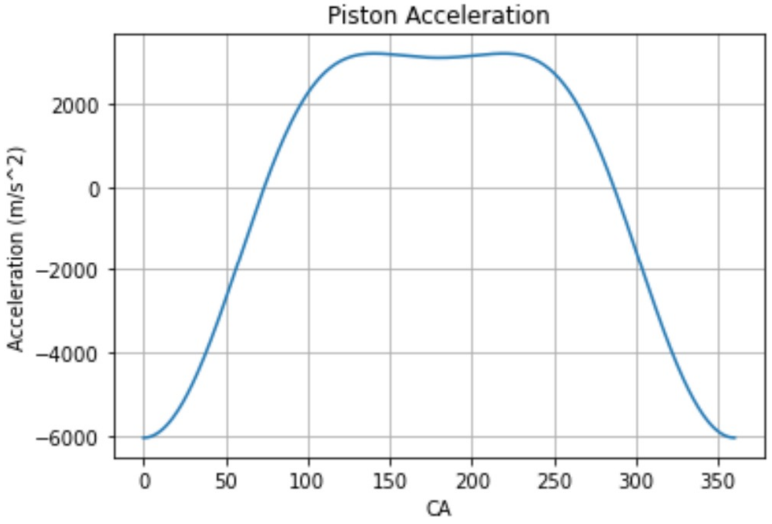
$$Q_{oil,axial} = \frac{-a_p h^3}{12\nu_{oil}} + \frac{V_{gas} h}{2}$$

Where h is the local oil film thickness, a_p is the piston acceleration



Under the influence of body force

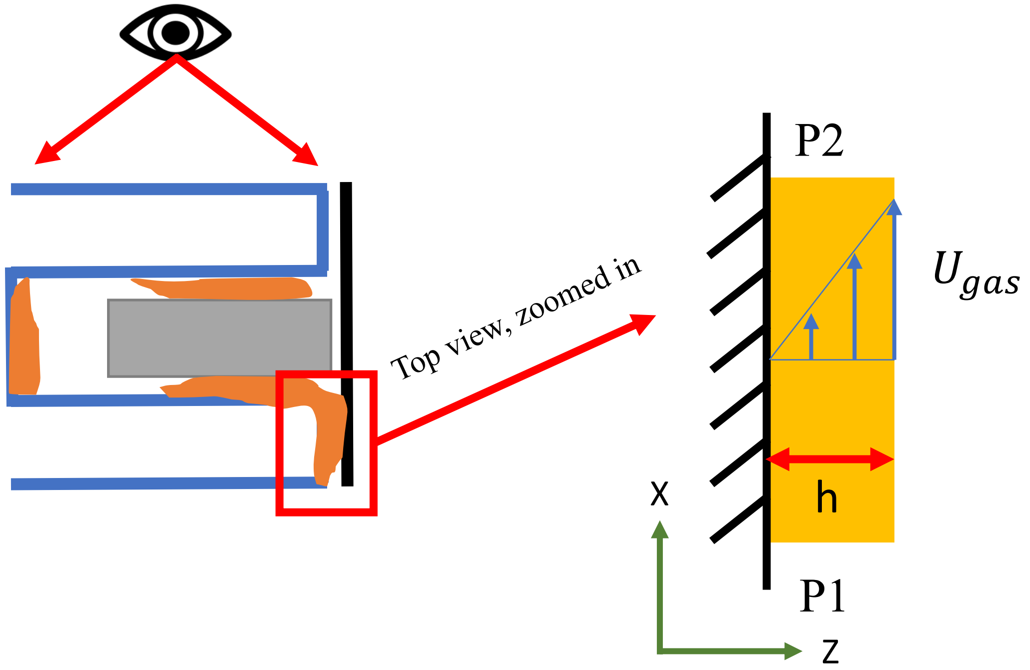
Piston acceleration, 3000 RPM



Numerical Modeling – Governing Equations

X-direction (circumferential direction)

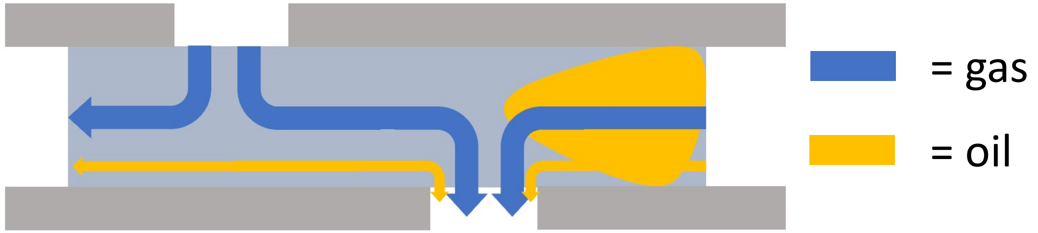
- Liquid oil motion governed by circumferential pressure gradient and gas flow
- Assumptions:
  - Flow is locally fully developed and steady
  - Film thickness (h) << piston circumference ($3e^{-6}$m/0.04099 m << 1)
  - Neglect variation of gas velocity in radial direction – oil velocity at gas-oil interface equals the gas velocity input at each point
- Model turns out to be a Couette-Poiseuille flow



Governing equation can be derived as

$$Q_{oil,circum} = \frac{-h^3}{12\upsilon_{oil}}\frac{\partial p}{\partial x} + \frac{U_{gas}h}{2}$$

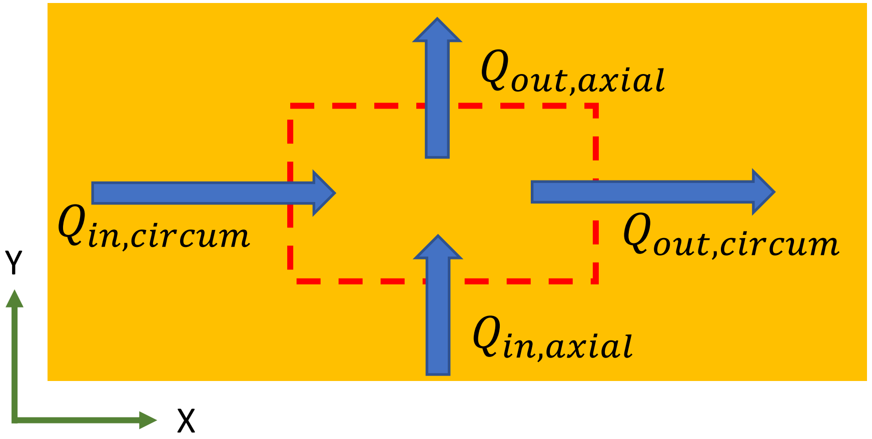
Where h is the local oil film thickness



Typical gas and oil flow pattern during expansion stroke

Numerical Modeling – Grid Setup

Consider a finite control volume:



Mass conservation gives a 2D wave (hyperbolic) equation

$$\frac{\partial h}{\partial t} + \frac{\partial \theta}{\partial x} + \frac{\partial \varphi}{\partial y} = 0$$

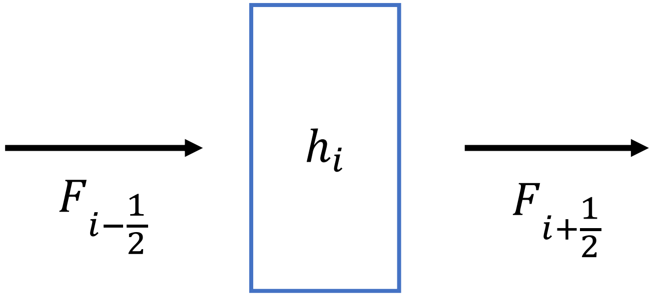
Where

$$\varphi = \frac{-a_p h^3}{12 v_{oil}} + \frac{V_{gas} h}{2}$$

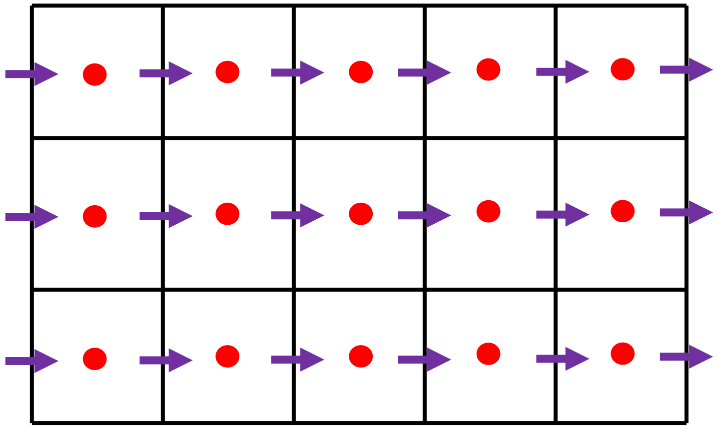
$$\theta = \frac{-h^3}{12 v_{oil}} \frac{\partial p}{\partial x} + \frac{U_{gas} h}{2}$$

Using a finite-volume implementation (circumferential direction shown)

$$\frac{\partial h}{\partial t} = \frac{1}{\Delta x}\left(F_{i-\frac{1}{2}} - F_{i+\frac{1}{2}}\right)$$



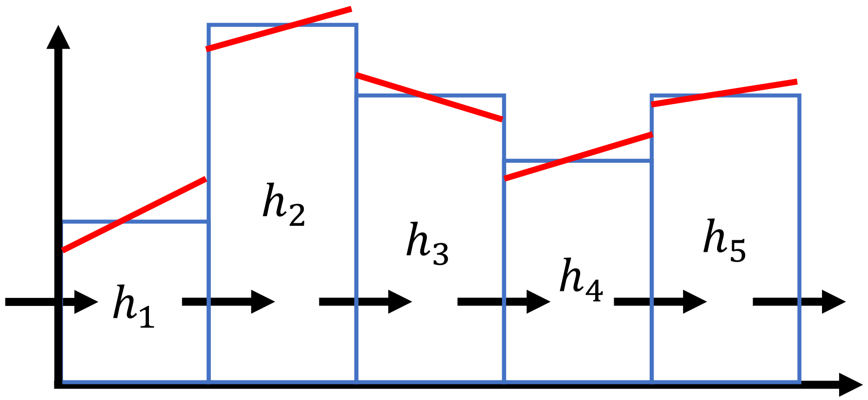
Grid setup using a staggered arrangement:



Local oil film thickness and velocity values are stored at the center of a node

Pressure is stored at the boundary so that local pressure gradient can be computed easily

Numerical Modeling – Shock Capturing



Piecewise linear reconstruction

For a domain with 5 cells, flux values needs to be evaluated at 6 boundaries. The value h right at a boundary is discontinuous (where σ is the slope within a cell):

$$h^L_{i-\frac{1}{2}} = h_{i-1} + \frac{\Delta x}{2}\sigma_{i-1}$$

$$h^R_{i-\frac{1}{2}} = h_i - \frac{\Delta x}{2}\sigma_i$$

Example of a shocks

Slope limiting (Monotonized Centered) to capture shocks:

$$\sigma_i = \frac{1}{\Delta x}\begin{cases} \min\left(2|h_i - h_{i-1}|, \frac{1}{2}|h_{i+1} - h_{i-1}|, 2|h_{i+1} - h_i|\right), if\ sign(h_i - h_{i-1}) = sign(h_{i+1} - h_{i-1}) = sign(h_{i+1} - h_i) \\ or \\ 0, otherwise \end{cases}$$

Flux at a certain boundary is given by the Riemann solver (essentially an upwind scheme)

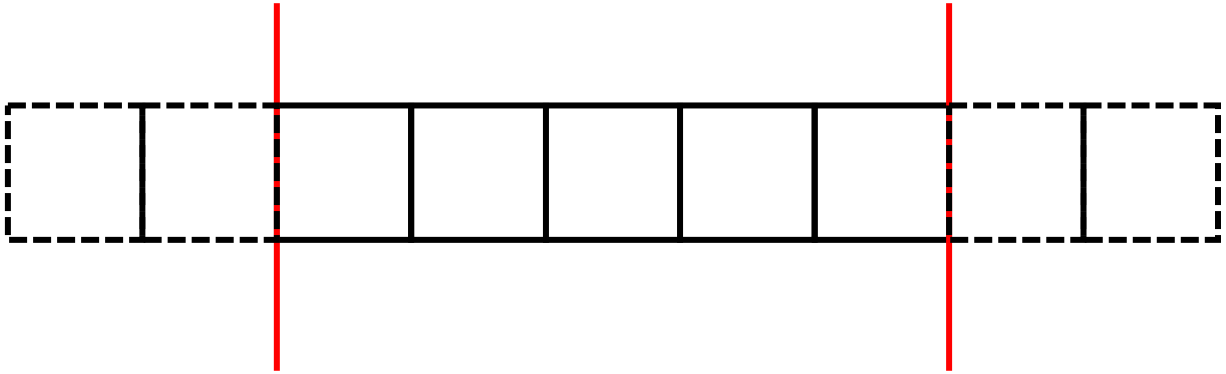
$$f\left(h^L_{i-\frac{1}{2}}, h^R_{i-\frac{1}{2}}\right) = \begin{cases} min_{h^L \le h \le h^R}(f(h)), & h^L \le h^R \\ max_{h^R \le h \le h^L}(f(h)), & h^R \le h^L \end{cases}$$

Numerical Modeling – Boundary Conditions

Apply temporal discretization (explicit Euler):

$$h_i^{n+1} = h_i^n + \frac{\Delta t}{\Delta x}\left(F_{i-\frac{1}{2}} - F_{i+\frac{1}{2}}\right)$$

Flux values at the 2 boundaries of a cell are given by the Riemann solver. The computation domain is

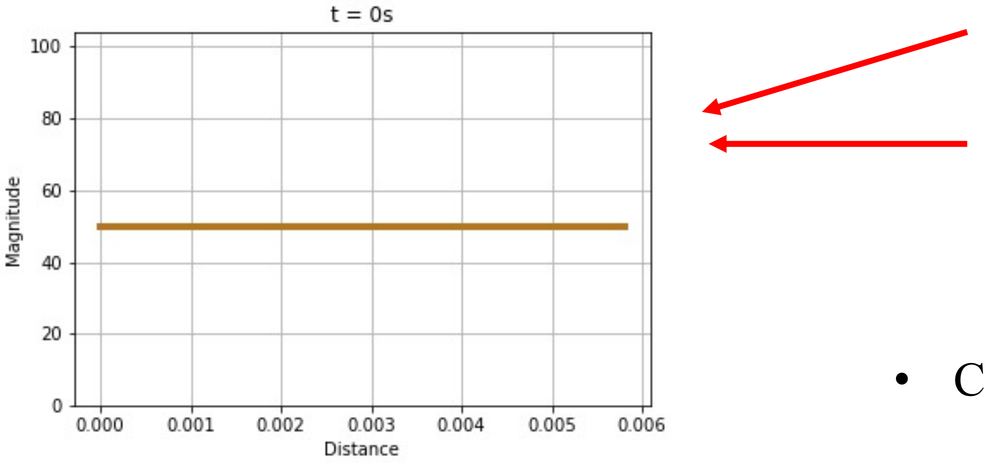


2 ghost cells are added to each of the extreme of the computation domain because the MC slope limiter needs information from those

Boundary condition:

- Axial
  - *Outflow*: linear interpolation of neighboring cells
    - $h_0 = 2h_1 - h_2,\ h_{-1} = 2h_0 - h_1$
  - *Inflow*: ghost cell values set to 0 if no oil is flowing in
  - Depending on ring location, some regions along the circumference are treated as *no flux boundary*

- Circumferential: periodic boundary condition



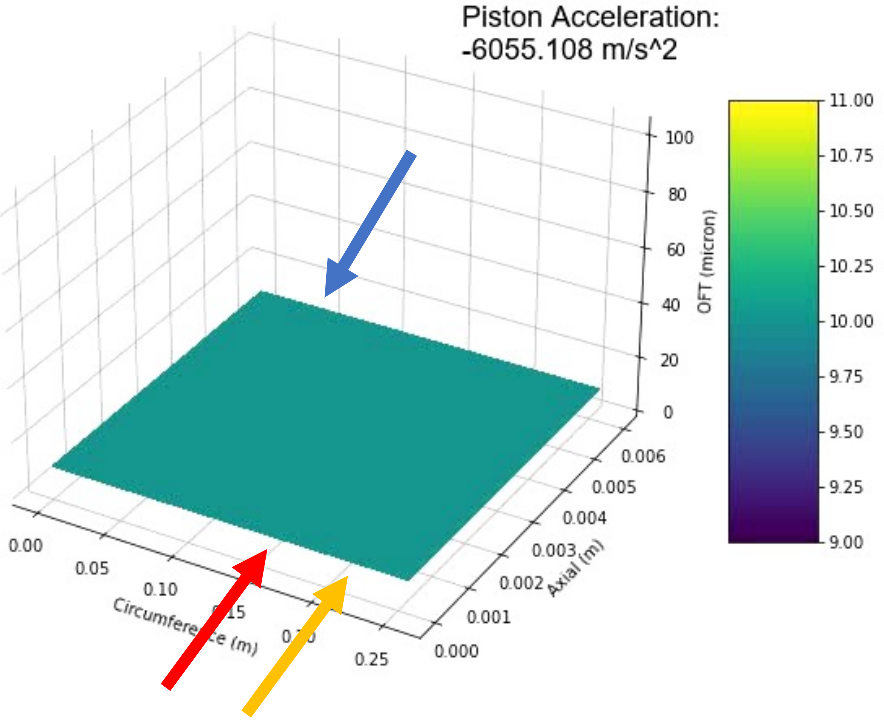
Simple oil-gas interaction with $U_{gas} = 10m/s$

Numerical Modeling-Results

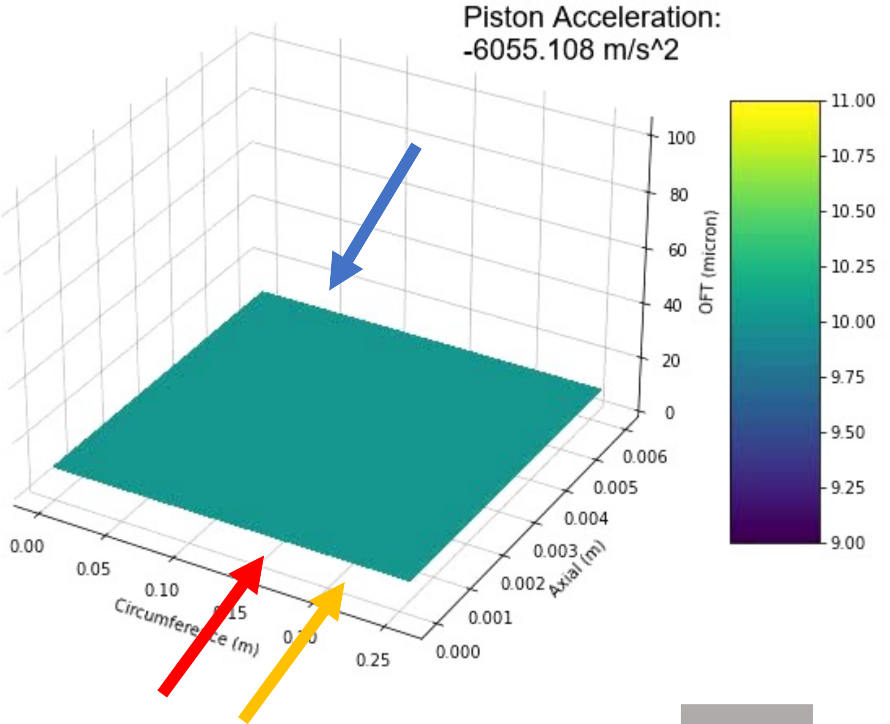
Results for the oil distribution on second land for an engine @ 3000 RPM (showing results for 3 engine cycles). Oil kinematic viscosity: $0.0016\ m^2/s$

→ Top ring gap → Second ring gap → Additional oil supply: 72 g/h

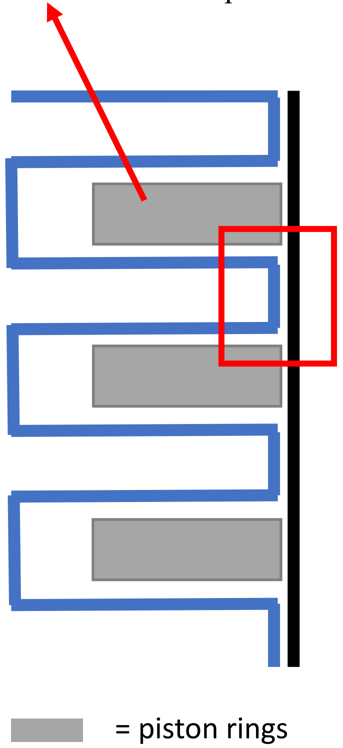
Depending on the position of the piston ring, boundary can be closed or open



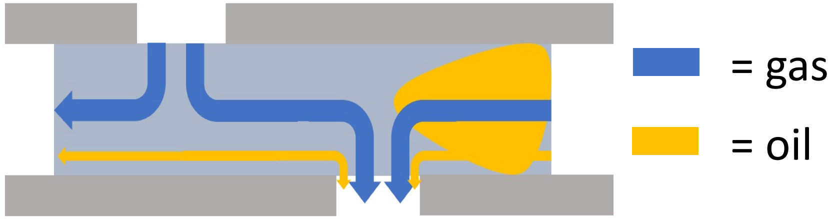
Open boundary on top and bottom



Top closed (except at piston ring gap), bottom open



▬ = piston rings

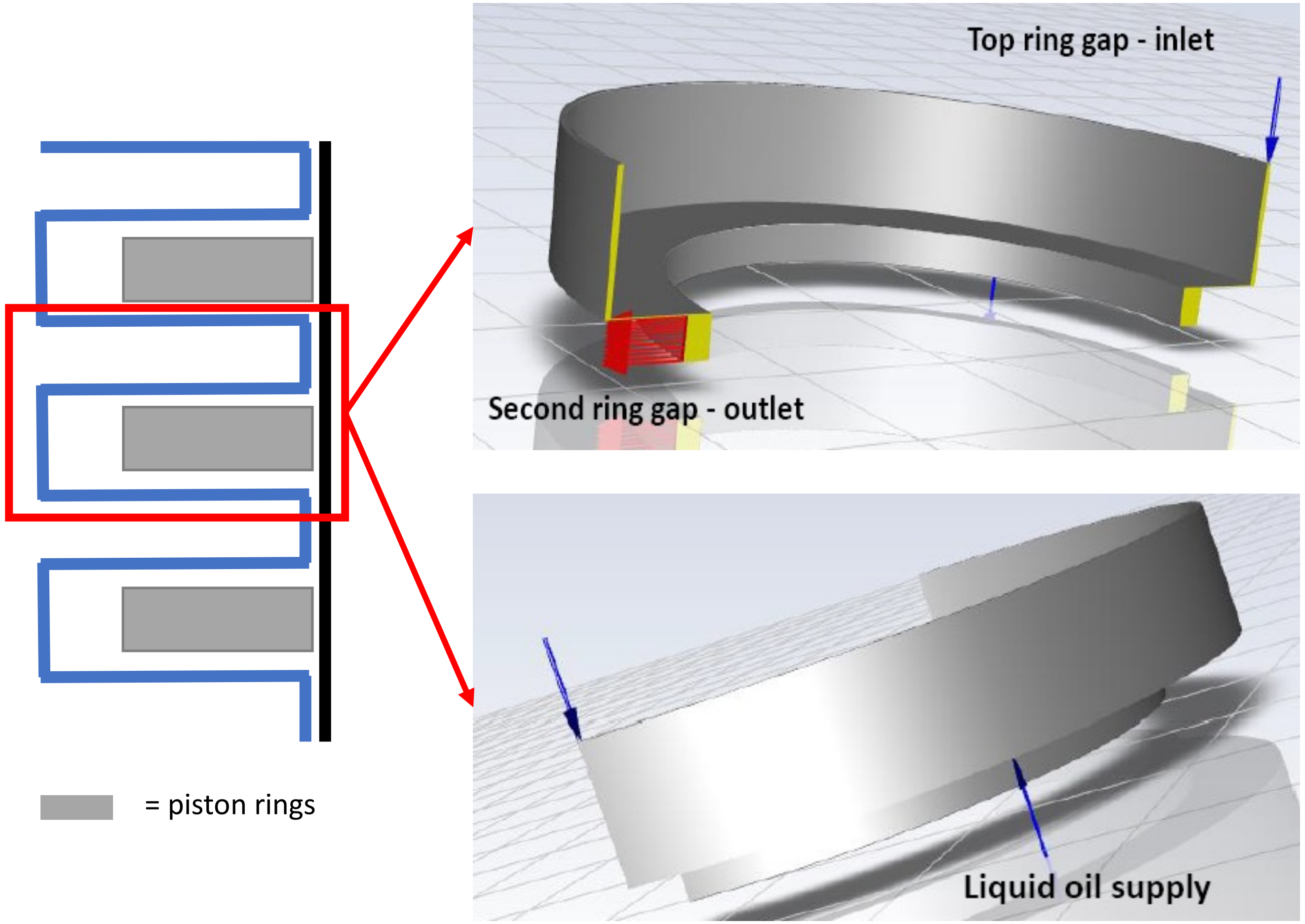


▬ = gas

▬ = oil

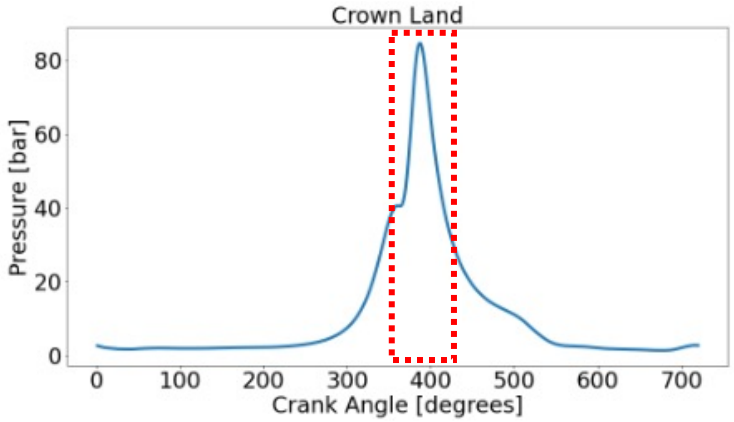
CFD Simulation (High Pressure Period)

Domain setup: second land and second ring groove, with second ring sitting at the bottom of the second ring groove

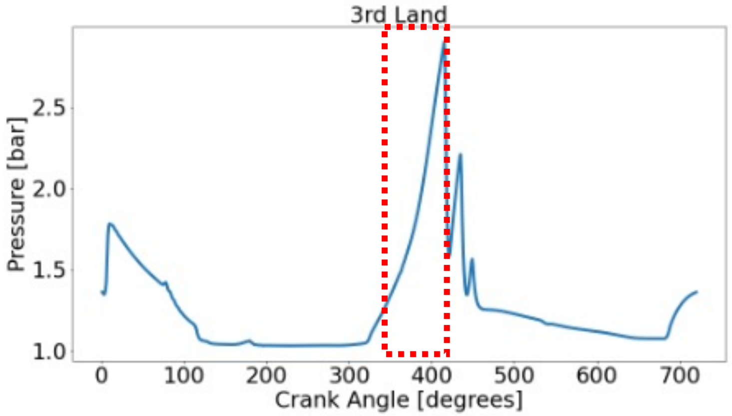


Boundary conditions settings

Pressure inlet:

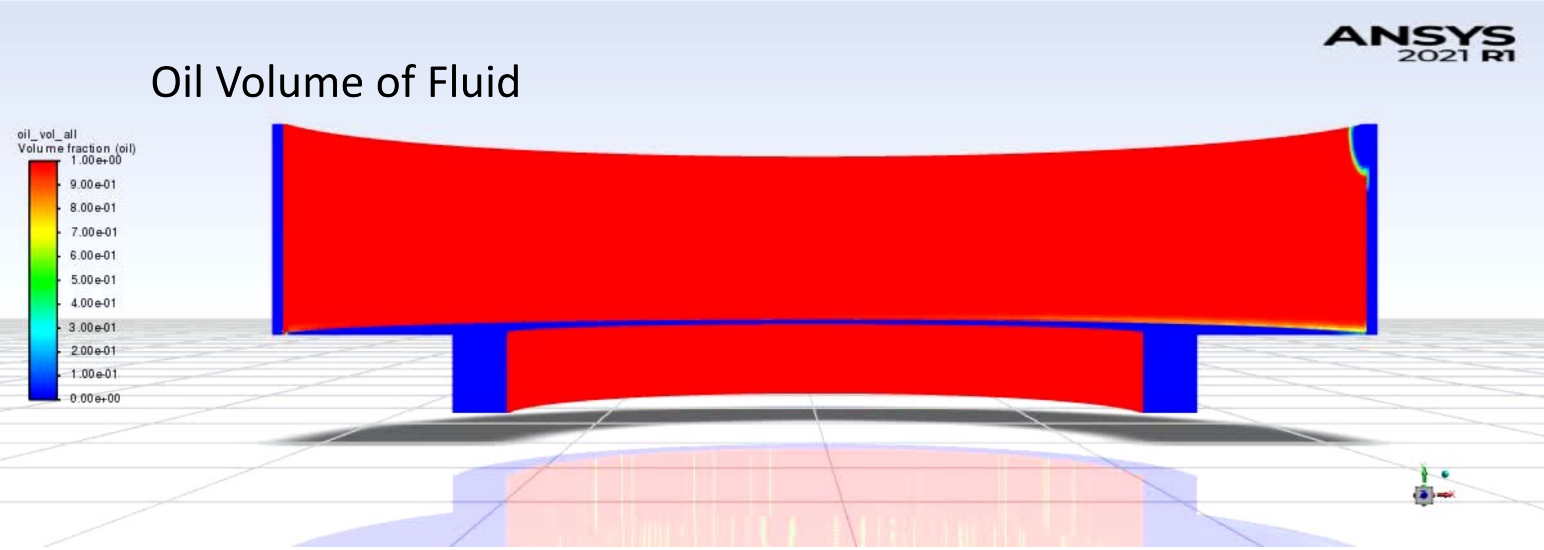


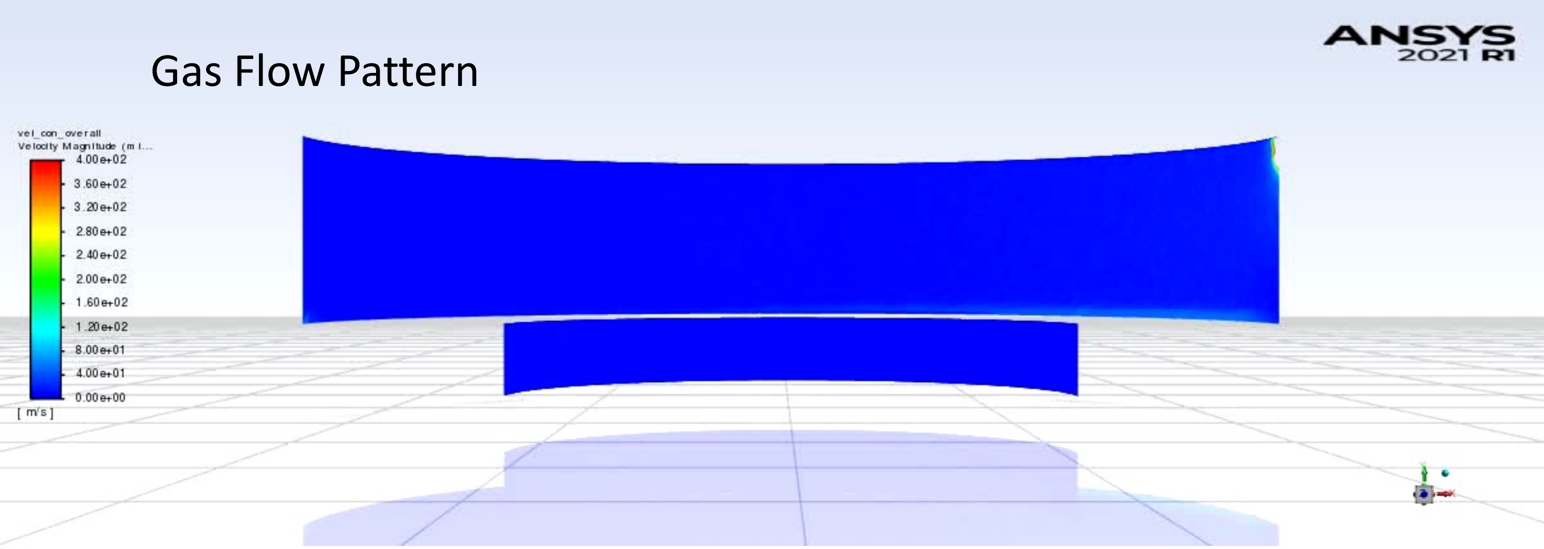
Pressure outlet:



- Other considerations: piston acceleration, moving liner.
- Oil kinematic viscosity: 0.0016 m^2/s
- Initial film thickness on piston land and piston ring groove is 50 micron

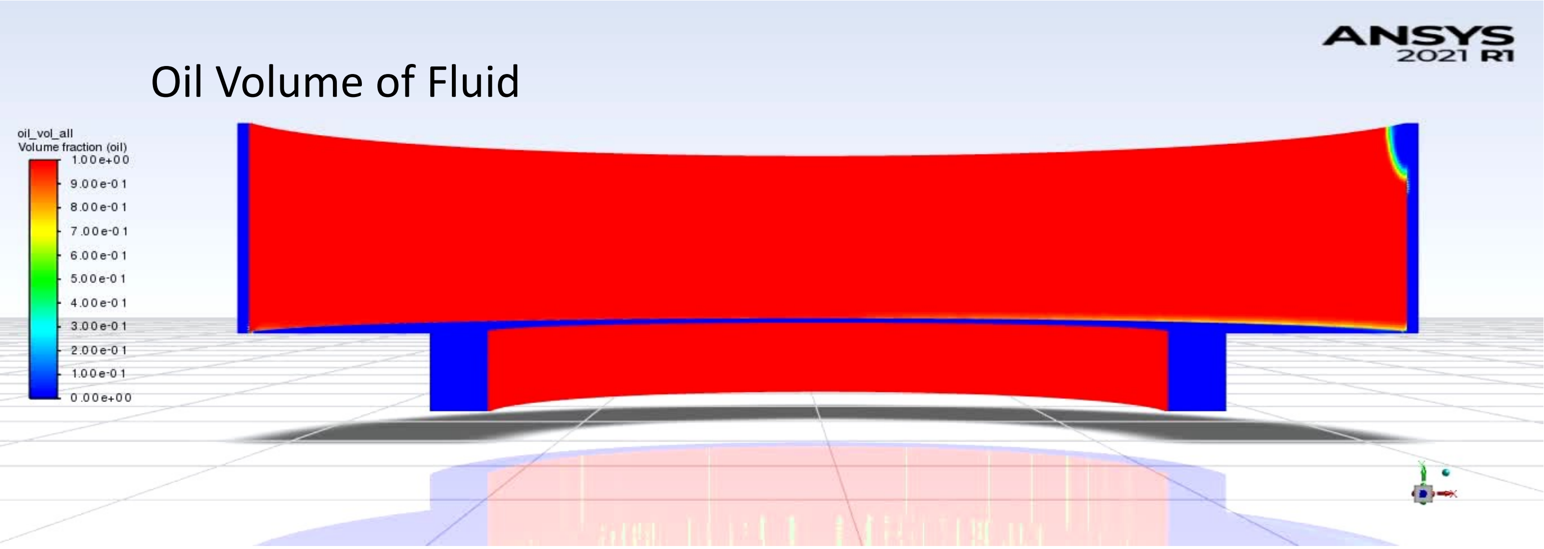
CFD Result (2nd Order, PISO, VOF)

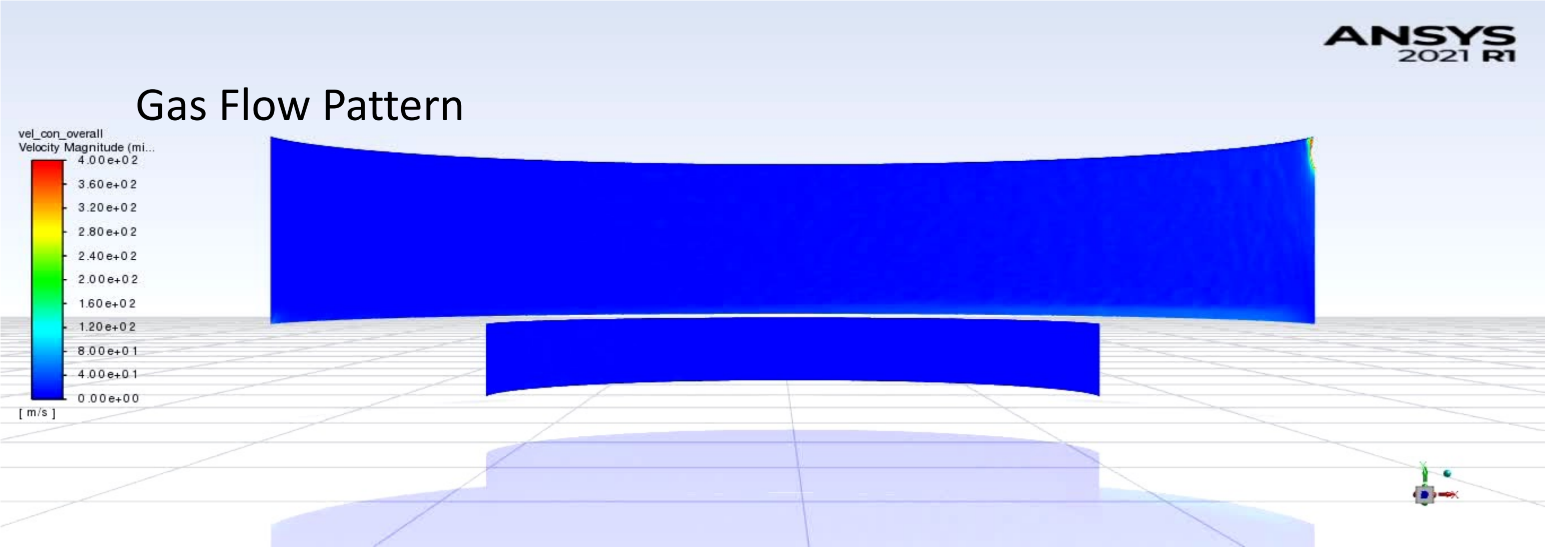

Oil Volume of Fluid


Gas Flow Pattern

1. Similar to what the numerical model predicts, regions close to the inlet will be depleted of oil.
2. Oil puddle being pushed to the top of the boundary due to inertia.
3. Gas flow around the inlet on piston land shows a strong recirculation pattern.
4. Gas flow in piston ring groove demonstrates strong vortex patterns as well.

CFD Result (1st Order, PISO, VOF)



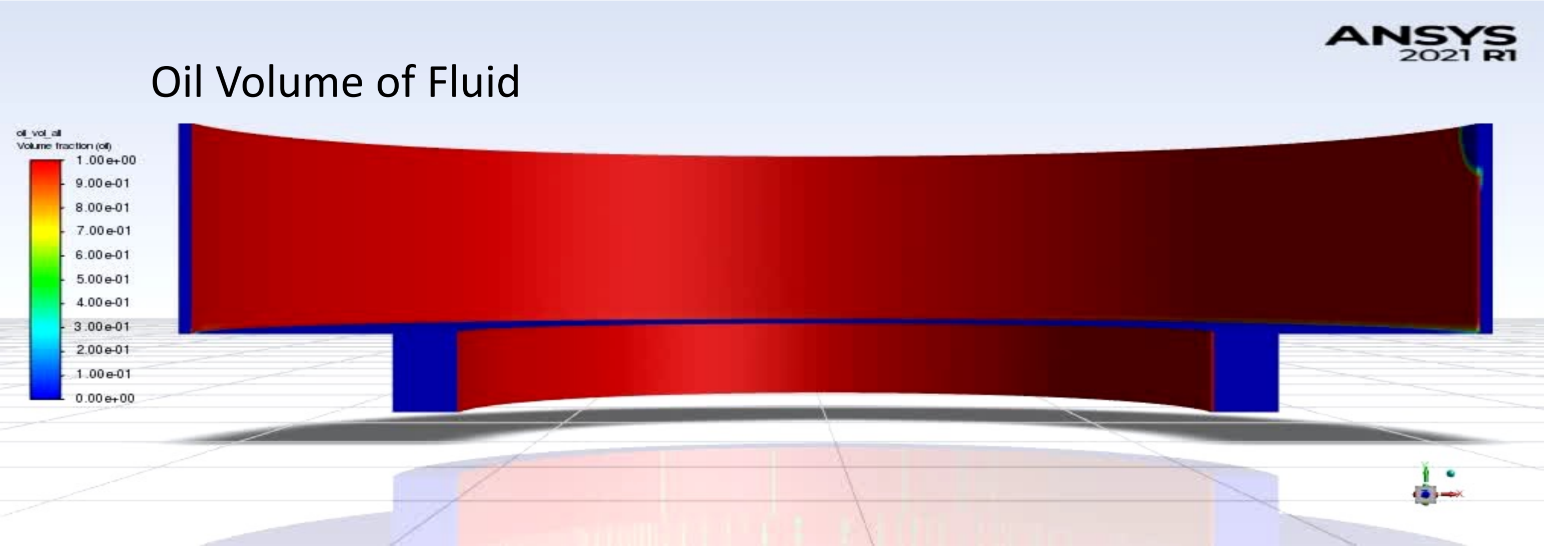


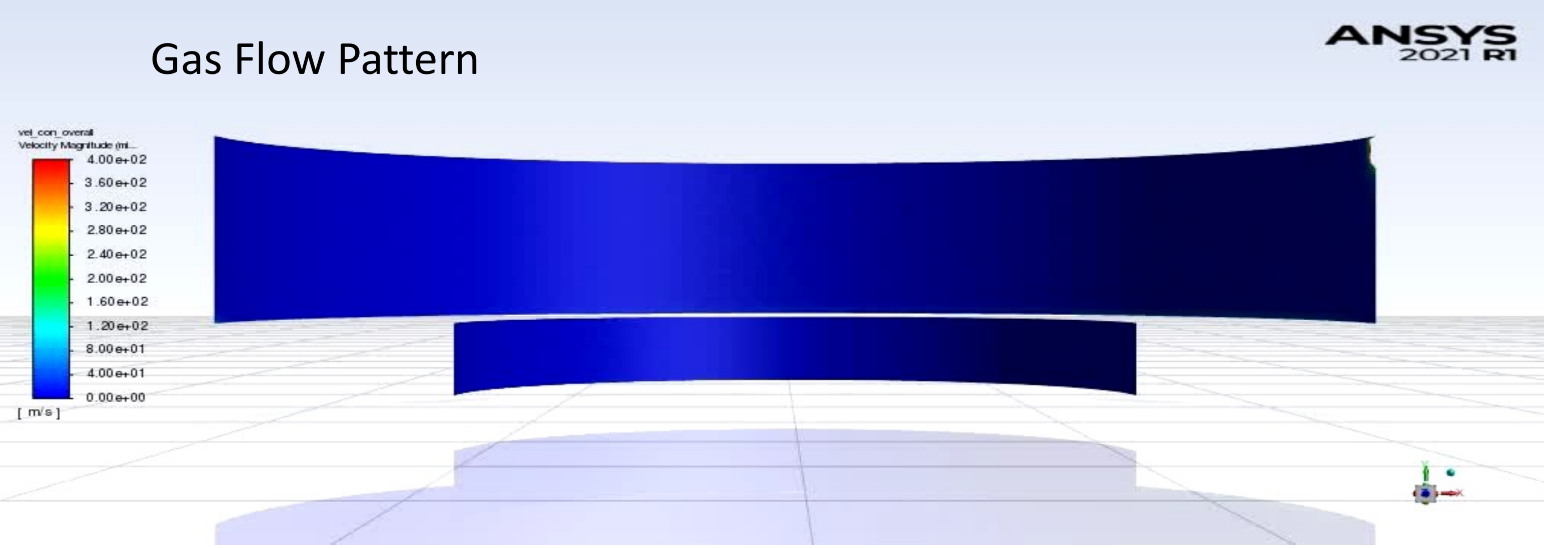
1. First order upwind (spatial discretization) PISO scheme shows much less detail in gas flow

    - Cell average VS linear reconstruction

2. Overall results are similar to 2nd order PISO

CFD Result (2nd Order, SIMPLE, VOF)





Lower level details of the velocity field might look different from the results by PISO scheme (in particular the recirculation region since velocity correction term u' does not contribute to pressure), but overall results between the two schemes does not demonstrate a large difference.

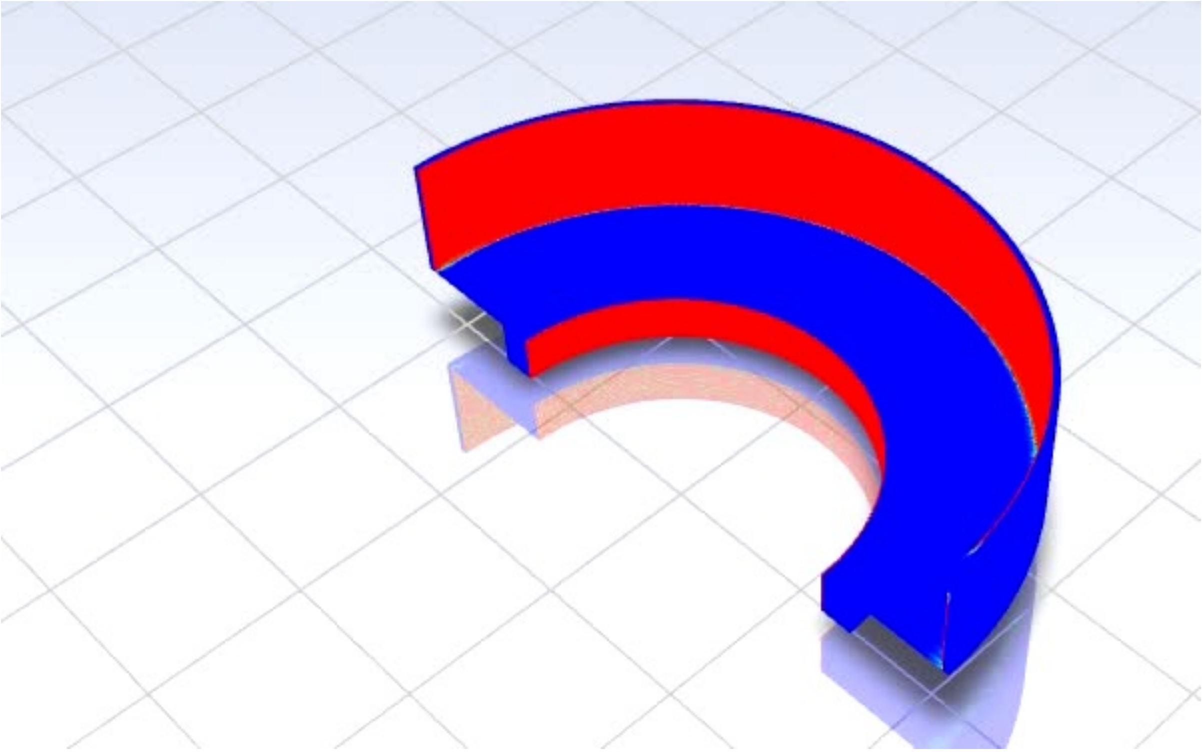
Conclusions and Future Works

What's observed:

1. Numerical model works as intended and demonstrates similar trend in oil transport (although with less detail) as CFD.
2. For CFD simulation, second order methods gives more details of the flow field. Difference between PISO and SIMPLE algorithm can be observed in recirculation region, but not very significant.

What's next:

1. Apply numerical model to other regions in piston ring pack system.
2. Perform CFD simulations using adaptive mesh refinement to capture small oil droplets.



VOF Isometric view, PISO, 2nd Order