EXPERIMENT AND NUMERICAL STUDY OF SUPERCRITICAL CARBON DIOXIDE FLOW THROUGH LABYRINTH SEALS

Haomin Yuan, Sandeep Pidaparti,
Mathew Wolf, Mark Anderson

SCO2 Symposium, Pittsburgh, PA
September 9 & 10, 2014

Outline

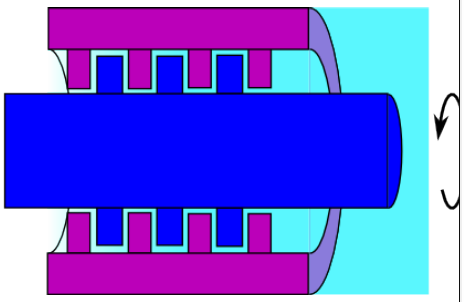
- Introduction
- Experiment facility
- Numerical method
- Results discussion
- Conclusion

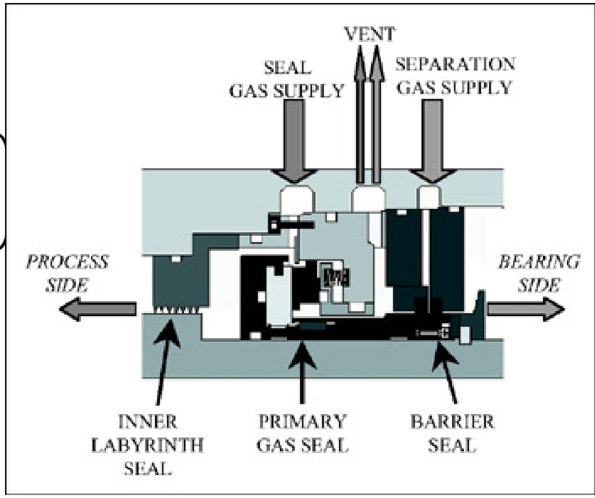
Introduction

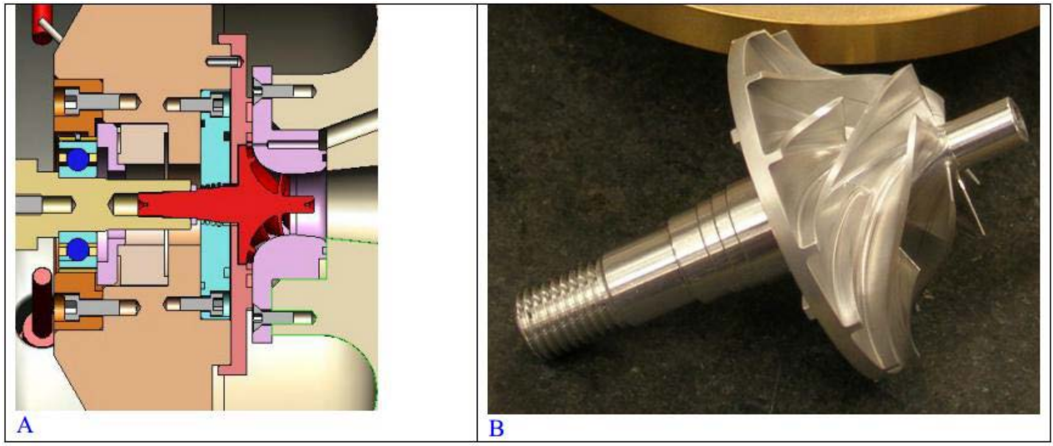
- Why labyrinth seal?

- Labyrinth seals are widely used in turbomachinery. Or used as a part of more complicated seals, such as dry gas seal.

- In Sandia SCO2 Brayton Cycle Experiment loop, simple labyrinth seal is used for compressor.

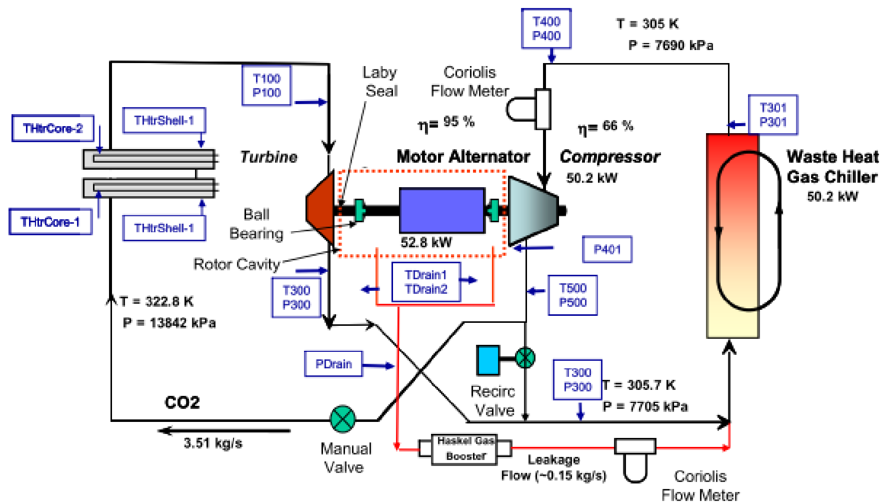


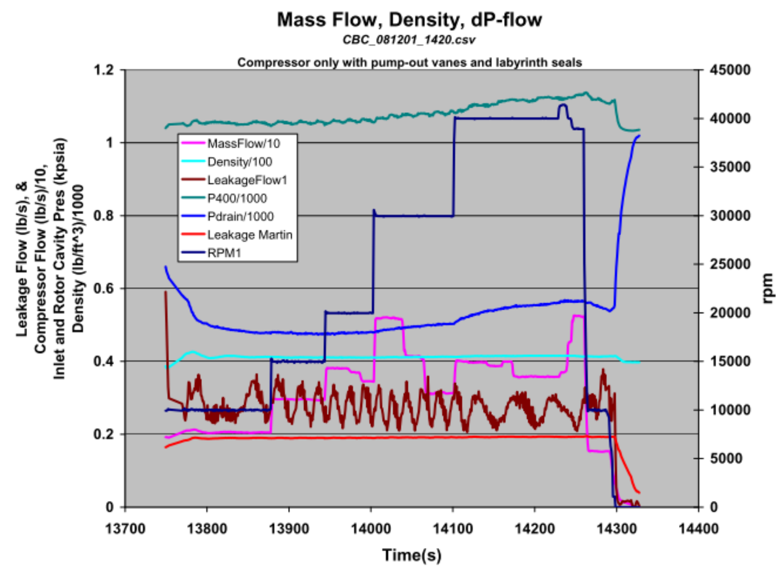




Introduction

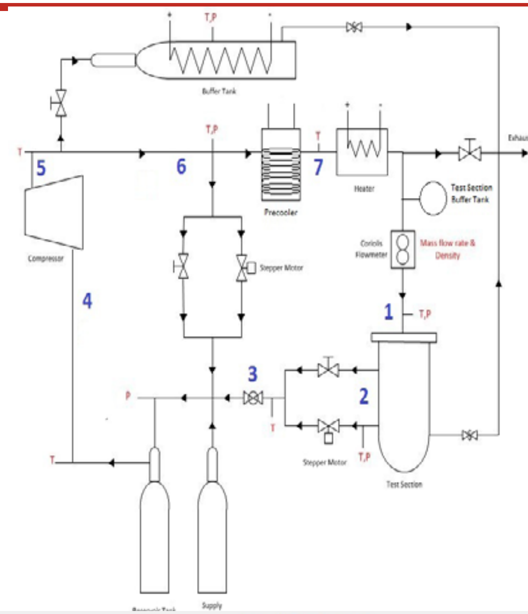
- Why new model?
- Old empirical methods based on incompressible fluid or ideal gas are not working for S-CO_2.
- As a result, new method is needed.
- This method should also applicable for future more complicated seal design for S-CO_2.
- Computational Fluid Dynamic code combined with S-CO_2 property is a good option.

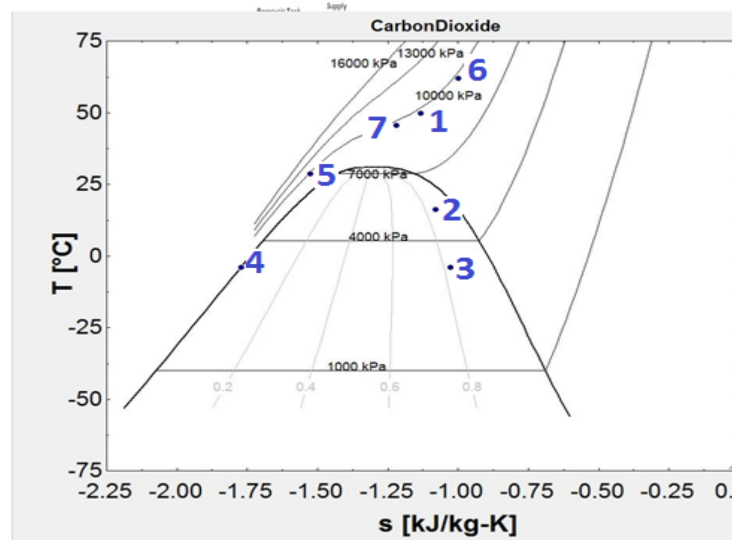




Experiment facility

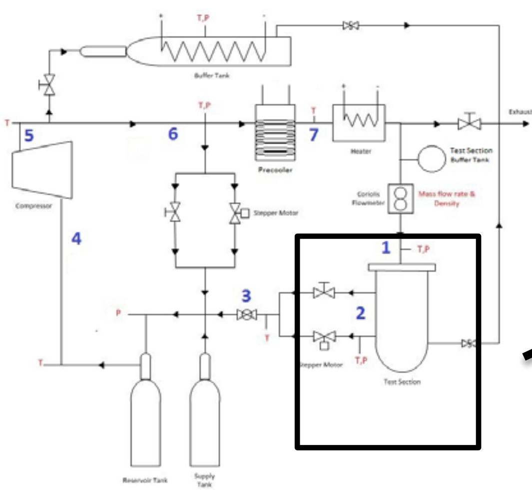
- A test facility was constructed at UW-Madison to measure the leakage rate through labyrinth seals.
- A Hydro-Pac single-stage compressor is used to compress CO_2 to supercritical state.
- Heater and cooler to help reach target inlet temperature.

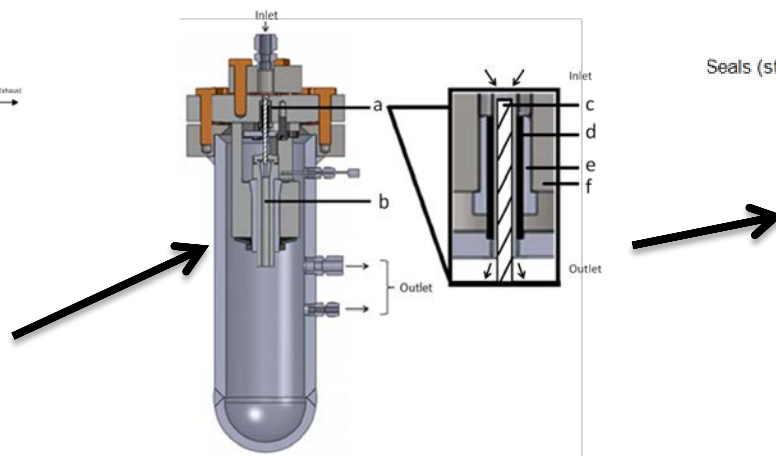


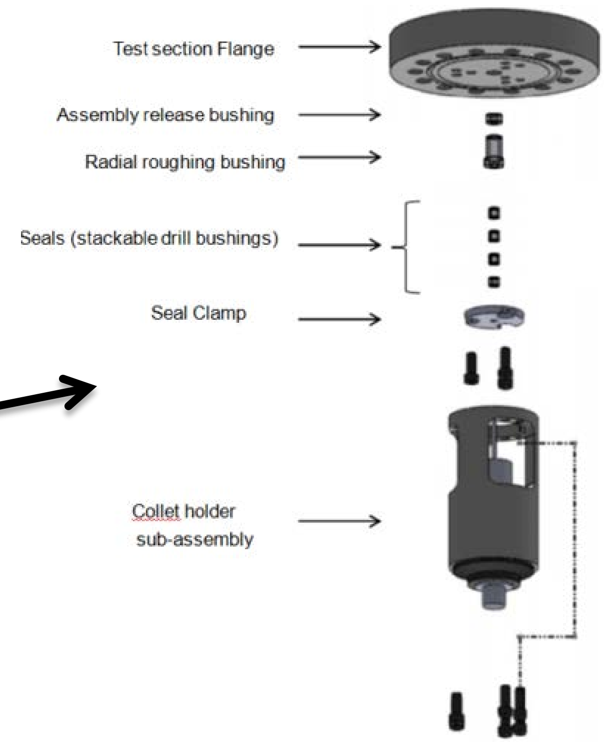


Experiment facility

- The test section is formed by a sub-assembly and a flange.
- Various labyrinth seal designs can be tested by changing the formation seals.
- A pressure vessel to help stabilize downstream condition.
- Flowmeters, thermocouples, pressure transducers are used to measure flow rate, temperature and pressure.

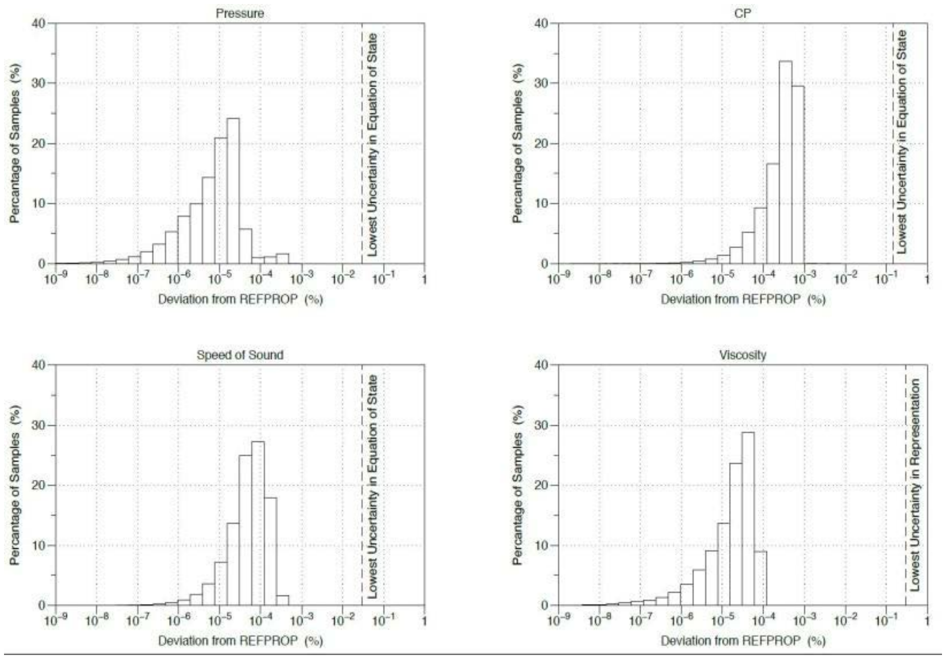






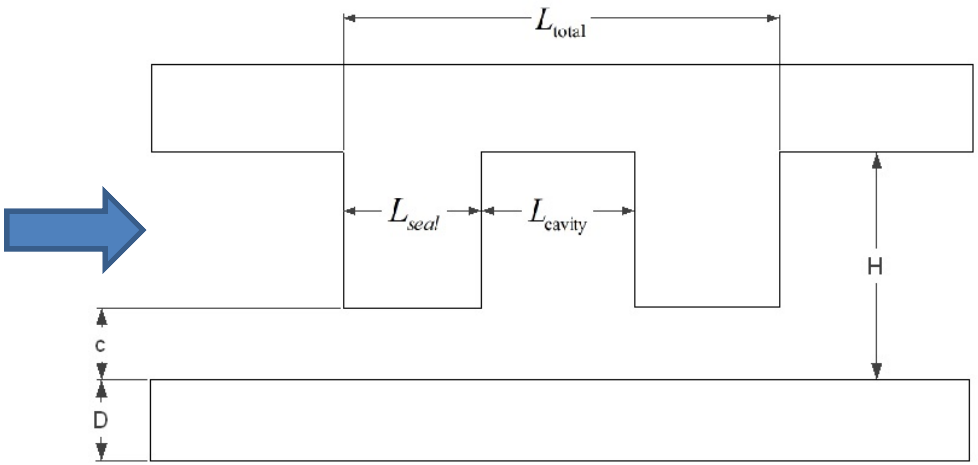
Numerical method

- OpenFOAM is used as the framework of numerical study.
- It is an open source CFD code, which brings a lot of flexibility.
- The compressible solver was modified to use S-CO_2 properties in simulation.
- The S-CO_2 properties were provided by a library called FIT, which is developed by Northland Numerics. FIT use an interpolated representation of properties based on REFPROP.



Numerical method

- Geometry.
- Currently, only see-through labyrinth seals are considered.



- As we can see, to define a see-through labyrinth seal, we need seven parameters.
- However, with one inherent correlation: $L_{total} = n*L_{seal} + (n-1)*L_{cavity}$
- The degree of freedom is six.

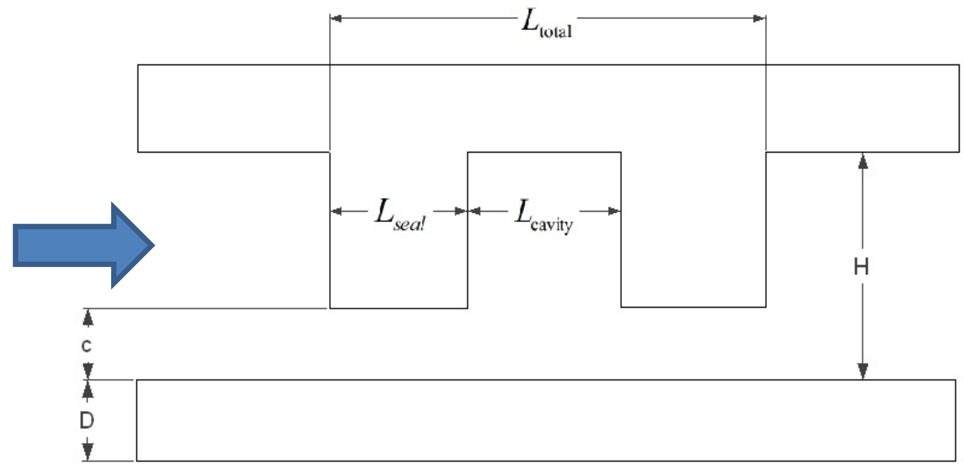
Description	Shaft diameter	Shaft clearance	Cavity Height(Cavity depth)	Cavity Length(Cavity width)	Seal Length(Tooth Width)	Total length	Number of teeth
Notation	D	c	H	L_{cavity}	L_{seal}	L_{total}	n
Value	3mm	0.105mm	0.88mm	1.27mm	1.27mm	3.81mm	2

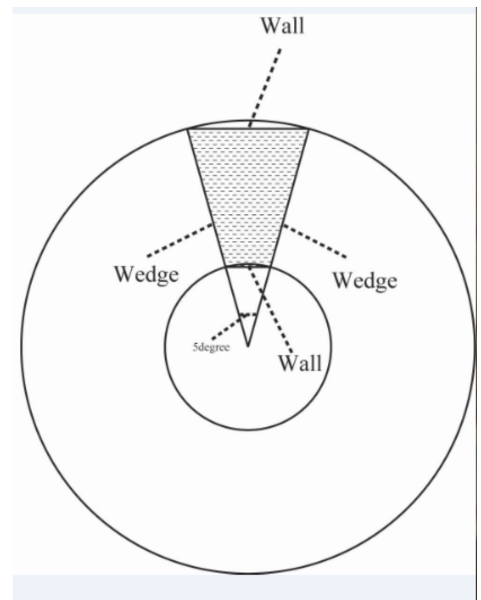
Numerical method

- SIMPLEC algorithm is used for pressure and velocity coupling.
- Standard k-epsilon model.
- Re~200,000

- Boundary condition
- To know the leakage rate corresponding to different pressure drop, fixed pressure is given at inlet and outlet. Fixed temperature is given at inlet.
- At wall, non-slip and adiabatic condition are set.

- To save computational time, pseudo-axisymmetric method is used.

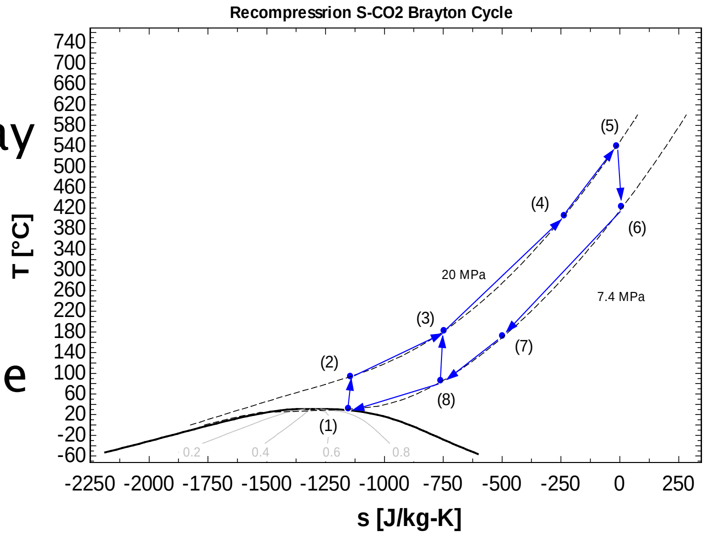




- Currently, the shaft is stationary

Numerical method

- In the discharge process, two-phase may appears when downstream condition is inside two-phase dome.
- In this research, homogeneous equilibrium model is used for two-phase modeling.

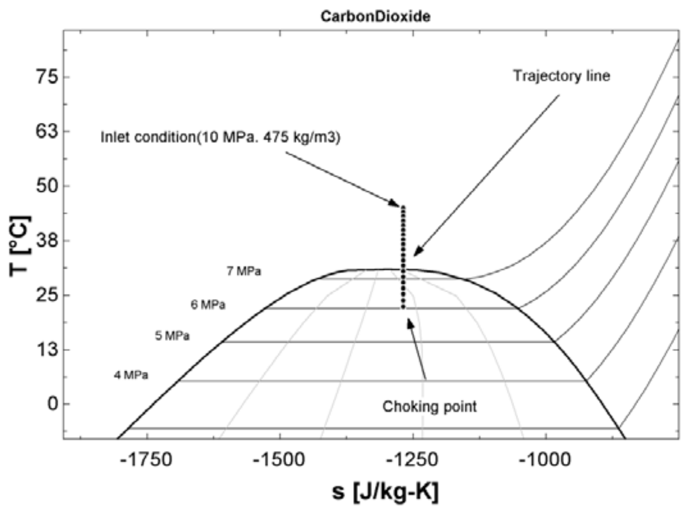


$$v_{two-phase} = x \cdot v_{gas} + (1-x) \cdot v_{liquid}$$

$$h_{two-phase} = x \cdot h_{gas} + (1-x) \cdot h_{liquid}$$

$$\mu_{two-phase} = x \cdot \mu_{gas} + (1-x) \cdot \mu_{liquid}$$

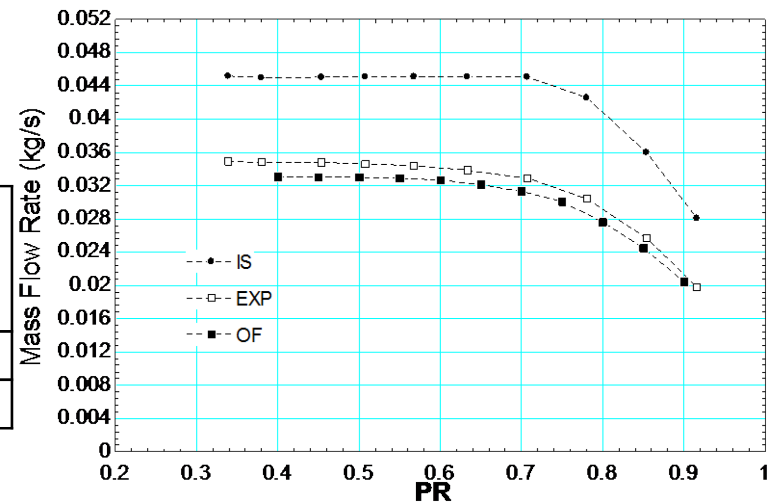
$$\kappa_{two-phase} = x \cdot \kappa_{gas} + (1-x) \cdot \kappa_{liquid}$$

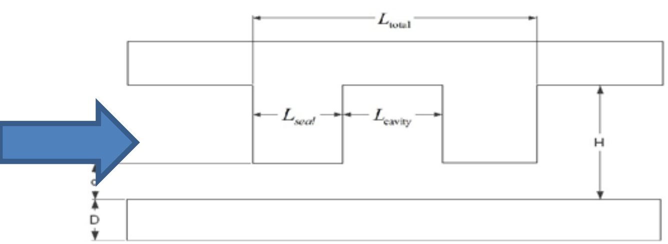


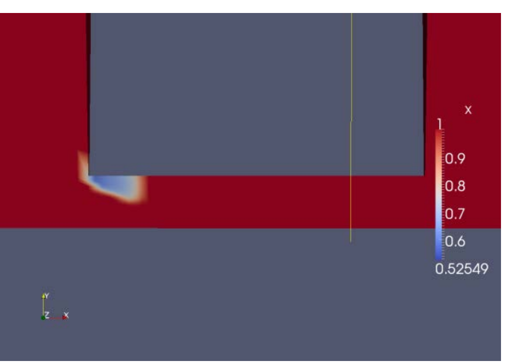
Results discussion

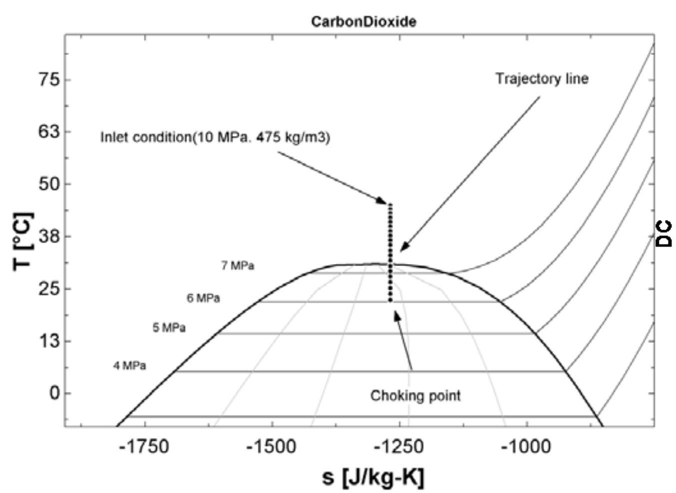
- A calibration case of two-teeth labyrinth seal are simulated and tested first at inlet condition of (10 MPa, 475 kg/m3)

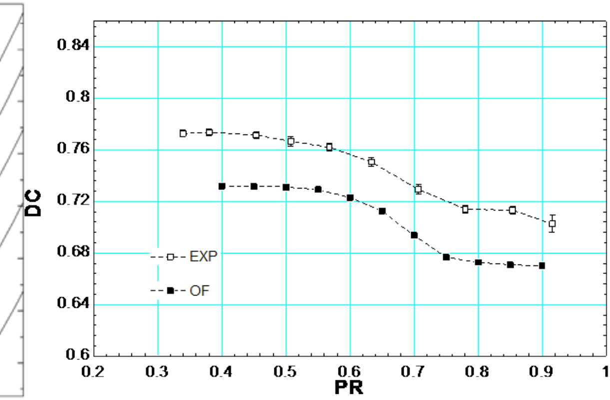
Description	Shaft diameter	Shaft clearance	Cavity Height(Cavity depth)	Cavity Length(Cavity width)	Seal Length(Tooth Width)	Total length	Number of teeth
Notation	D	c	H	L_{cavity}	L_{seal}	L_{total}	n
Value	3mm	0.105mm	0.88mm	1.27mm	1.27mm	3.81mm	2





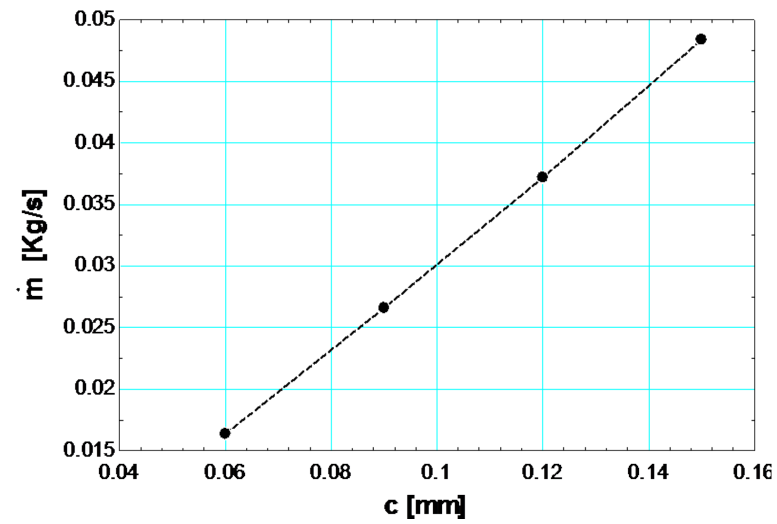


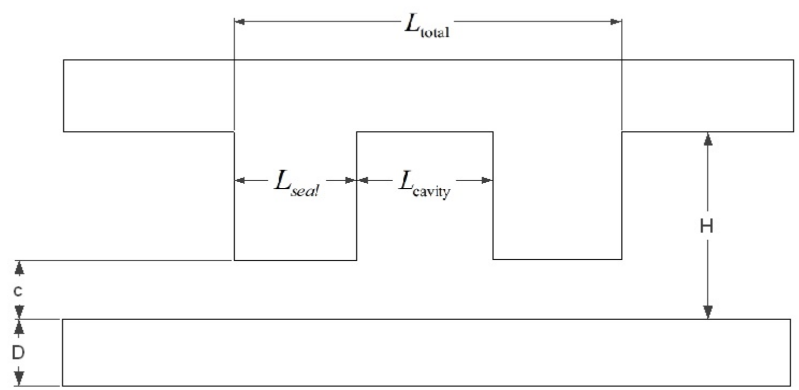




Results discussion

- Radial clearance (c)
- This parametric study is based on three-teeth seals.
- Inlet condition is (10MPa, 498 kg/m3), outlet pressure is fixed at 5MPa.
- These results show that as radial clearance increases, flow area increases, thus more mass can flow through the seal.

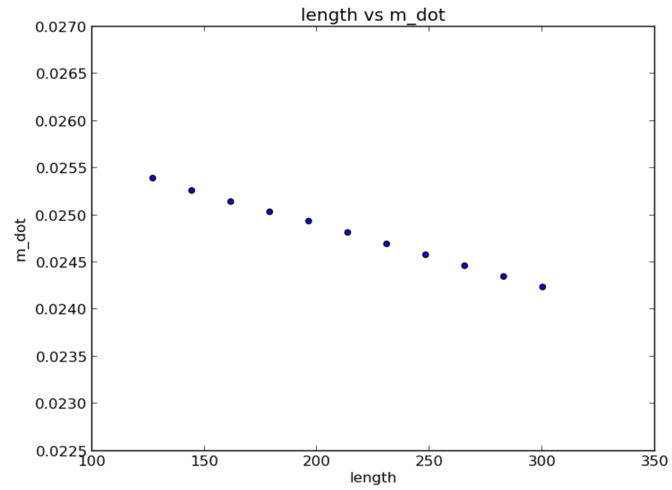


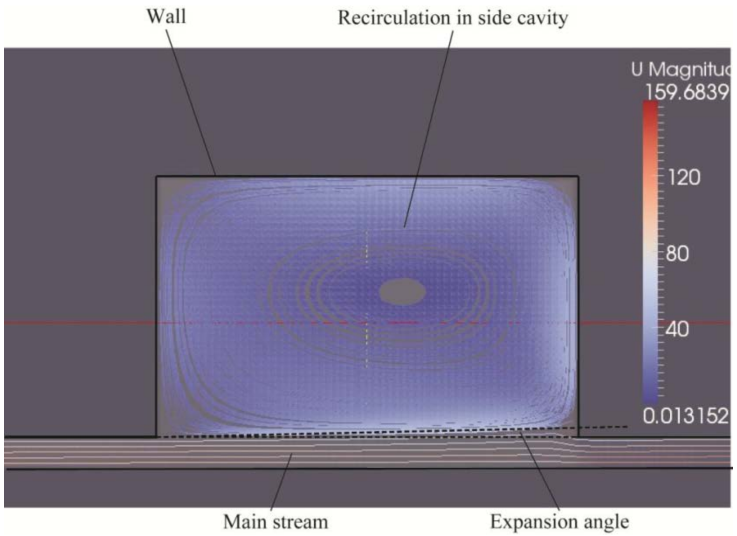


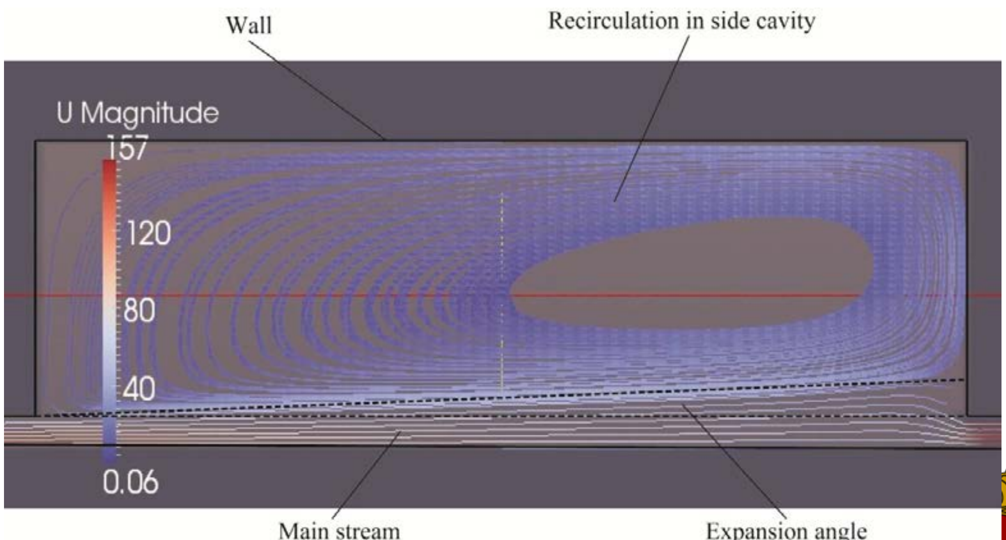
Results discussion

- Cavity length(L_{cavity})
- Total length is kept constant.
- L_{seal} is changed according to the change of L_{cavity}

- Larger L_{cavity} will results more radial expansion of main stream, which results a larger contraction form loss at next tooth.

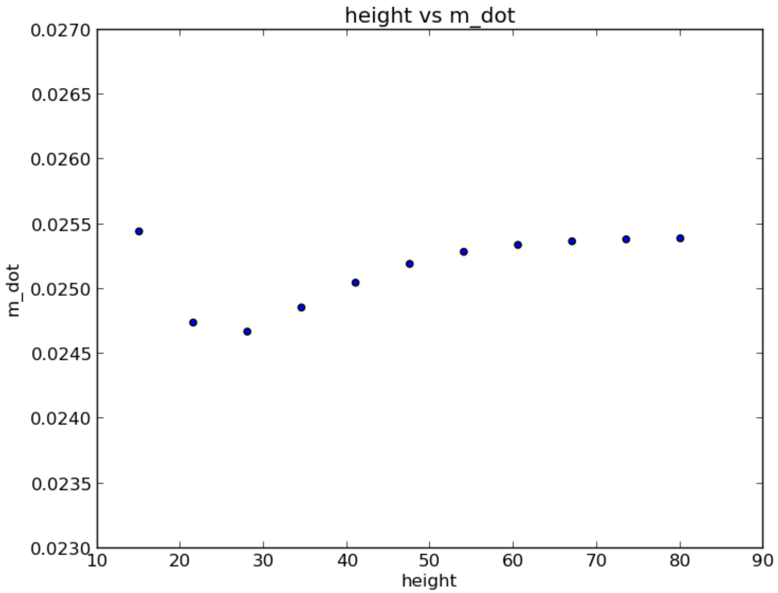


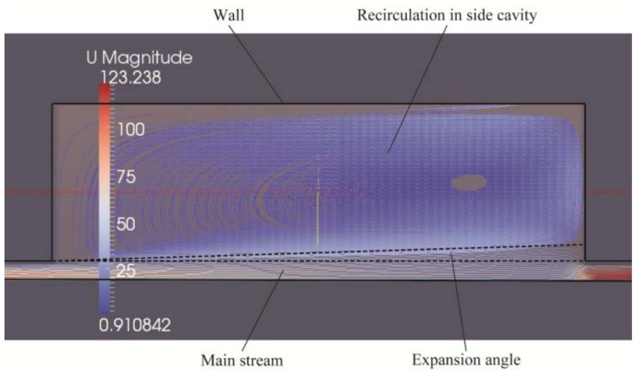


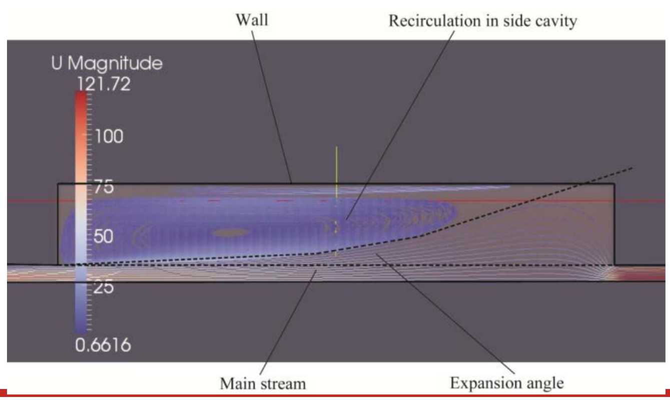


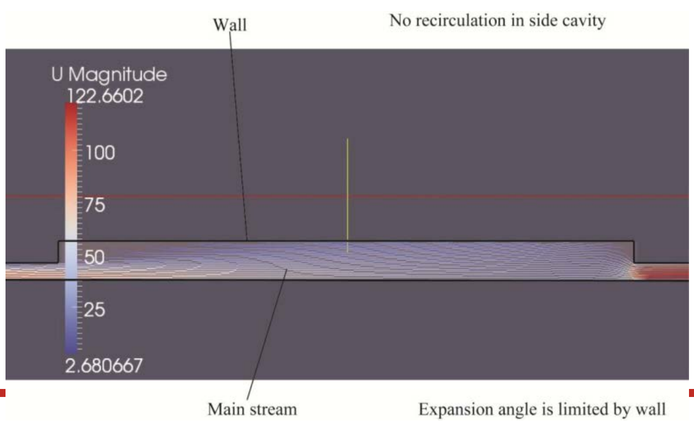
Results discussion

- Cavity Height (H)
- The effect of cavity height is relative complicated.
- As an optimum value of H results in minimum leakage.



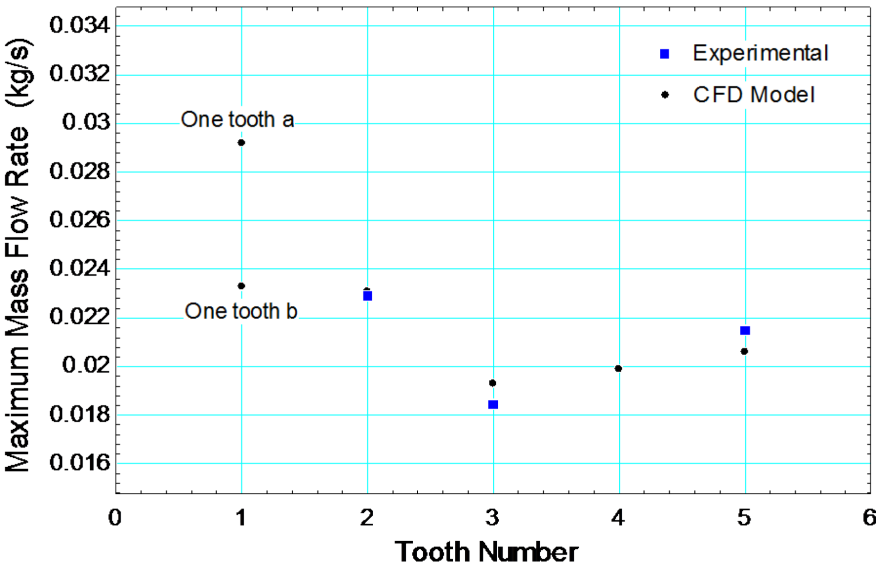


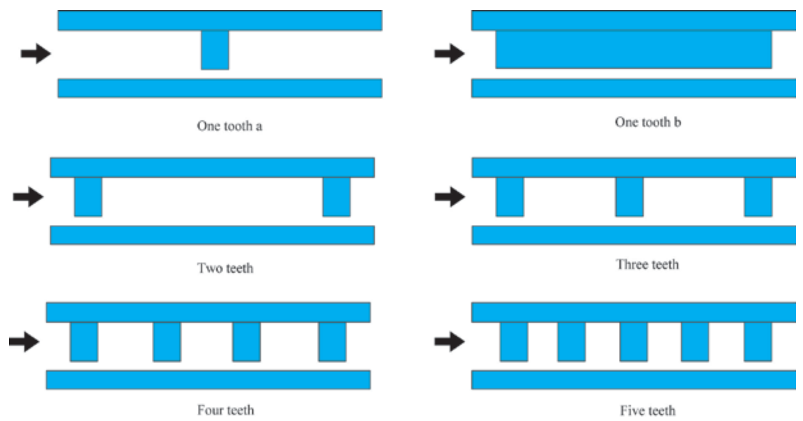




Results discussion

- Number of tooth (n)
- The total length and seal width are kept constant. Tooth is inserted one by one to see the change.
- Inlet condition of (10 Mpa, 325 kg/m3), outlet pressure of 5 Mpa.
- As more tooth in seal, more contraction form loss is introduced.
- However, the space between teeth is also reduced.





Conclusion

- Experiment facility was build in UW-Madison for various seal test for S-CO_2

- Experiment data can serve as a data base for future researchers.

- Numerical method is calibrated by experiment results

- Parametric study of several geometric parameters provides guiding for design optimization.

THANK YOU