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

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ABSTRACT

This paper presents a study of Supercritical Carbon Dioxide (S-CO_2) flow through labyrinth seals, both experimentally and numerically. An experiment facility has been constructed at UW-Madison to measure the leakage rate and pressure drop of S-CO_2 flow through labyrinth seals. Various geometries and conditions have been tested to study the flow characteristic and provide validation data for numerical study. The CFD simulation of this scenario is performed under the framework of an open source CFD code OpenFOAM. Fluid properties of S-CO_2 are implemented into the code. The primary goal is to verify the code's capability to predict leakage rate through seals, with a secondary goal focused on using the code to optimize the seal geometry for S-CO_2 flow, and understand how changing the operating condition will affect the performance of the seal. Optimization of the seal geometry is performed by studying the effects of geometrical parameters like radial clearance, tooth width, cavity depth, cavity width, and the number of teeth. It has been found that as the cavity width is increased individually the leakage rate through the seal decreases, whereas increasing the radial clearance causes an increase in the leakage rate. Cavity depth studies indicate that there is an optimum value that results in minimum leakage rate. For a fixed total seal length, as the number of teeth are increased reduction in leakage rate associated with the addition of teeth was overcome by the increase in leakage rate associated with the decrease in cavity width leading to a minimum leakage rate for optimum number of teeth. This phenomenon is also observed in experiment under the same conditions. The results obtained from this study will serve as a baseline to predict the flow behavior of S-CO_2 through other complex geometries in the future.

INTRODUCTION

Supercritical Carbon Dioxide (S-CO_2) is a promising working fluid for future high efficiency power cycles. However, the real fluid behavior of S-CO_2 near the critical point makes it challenging to perform experiments as the requirement for control and measurement is very strict. At the same time, it is also challenging to perform numerical study of S-CO_2 flow, which requires a highly accurate property database and a robust algorithm.

The idea of using labyrinth seals for turbomachinery has been around for a long time. From Sneck's (Sneck 1974) review paper, Parsons(Parsons 1938; Parsons 1921) first introduced the idea of using labyrinth seals. The idea was to introduce a tortuous flow path between high and low pressure regions by means of a series of non-contacting restrictors and separating chambers (Sneck 1974). By this method, the pressure head is converted into kinetic energy and dissipated by the recirculation in these chambers.

After Parsons's original designs, various researchers have performed studies on labyrinth seals from different perspectives. Several works are mentioned here as milestones. In the pioneering paper by Martin (Martin 1908), labyrinth seals were considered to be a series of discrete throttling processes. Martin assumed that the kinetic energy carry over is equal to one. Egli(Egli 1935) made a modification of Martin's labyrinth seal model by introducing a kinetic energy carry-over coefficient, which is determined empirically in his work. The carry-over coefficient represents the portion of kinetic energy carried from one cavity to the next. Egli also noticed that since the pressure drop across each restrictor increases, the last restrictor is the first to reach the choked flow pressure ratio. Hodkinson et al (Hodkinson and Mech 1939) assumed a conically shaped stream in each cavity from a fluid mechanical point of view. The expansion angle of this conically shaped stream determines the carry-over coefficient in Egli's model.

Eldin(Eldin 2007) conducted the most recent and significant work regarding to labyrinth seals. Even though his experiment used air as the working fluid, some of his conclusions are observed in this research. He mentioned that increasing the seal blade thickness reduces leakage by the largest amount (but total length of the seal is changed). Increased eccentricity leads to increased leakage rate, but this effect is only significant at low Reynolds number. The effect of cavity depth (i.e. cavity height in this research) was minor compared to seal blade thickness although there does exist an optimum cavity depth which results in a minimum leakage rate.

Regarding CFD simulations of labyrinth seals, Wittig et al(Wittig et al. 1987), Rhode et al(Rhode, Ko, and Morrison 1994), and Schramm et al(Schramm et al. 2004) did extensive research in this area. They directly used CFD tools to do optimization for different kinds of labyrinth seals, including staggered, stepped, and see-through. However, they used the ideal-gas assumption in their research which makes their methods improper for this problem. Suryanarayanan(Suryanarayanan 2009), also used ideal gas, on the other hand presented a new model to calculate the carry-over coefficient in Hodkinson's model(Hodkinson and Mech 1939).

A recent study by Jiang et al(Jiang et al. 2011) presents a numerical study on vane, gland, and shaft seals for supercritical water. They used finite element method to solve fluid dynamic equations to find the value of rotordynamic coefficients for these seals. In their research, they focused on the steam forcing induced by the leakage, and the effect from different parameters like the tooth number, seal clearance, etc. However, leakage rate prediction and two phase capability were not mentioned in this paper. In the current phase of this research, leakage rate prediction is our main focus. Due to the possible appearance of two-phase scenario, simple Homogeneous Equilibrium Model (HEM) was implemented. In the future work, bearing force, rotordynamic coefficient study, stability analysis, and the effect of two-phase on them will be included.

In this research, we used both experiment and CFD techniques to study this problem. However, only see-through labyrinth seals are considered currently. A test facility was constructed at UW-Madison to perform experiment(Edlebeck 2013; M. Wolf, Yuan, and Edlebeck 2013). And the data from this facility was used to validate the numerical study. For the numerical simulations, an open source CFD code OpenFOAM was used as modification and implementation of user-defined property is easier compared to other commercial codes. As the S-CO_2 flows through labyrinth seals, two-phase scenario may occur depending on the inlet condition and pressure drop. In order to handle this situation, we used the homogeneous equilibrium model (HEM) to simulate two-phase flow. In previous research, simple geometries like orifice and annular seal have been tested and the numerical code showed good agreement with the experiment data(Yuan et al. 2013). In this paper, we investigated the more complicated geometry, labyrinth seals.

TEST FACILITY

The UW-Madison Seal Test Facility is logically depicted in figure 1. It was used to measure the leakage rate and pressure drop in seal geometries under S-CO_2 conditions. The facility allows for a wide variety of geometries and inlet conditions to be tested. As can be seen, a single-stage compressor made by Hydro-Pac is used to raise the pressure of CO_2 above critical pressure (7.38 *MPa*). The outlet of the compressor is connected to a buffer tank which is a large volume tank used to minimize the pressure fluctuations due to the compressor cycling and enhance the stability of the whole system. After the compressor, the flow passes through precooler and preheater stages. The precooler and preheater are automatically controlled to cool or heat the fluid to the target temperature. Before the test section, the flow goes through a flow meter where both the density and mass flow rate are recorded. Thermocouples and pressure transducers are placed before and after the test section to measure the upstream and downstream conditions, corresponding to states 1, 2 in figure 2. After the flow passes through the test section, it enters a reservoir tank to help attain a stable downstream condition. The flow then returns to the inlet condition of the compressor.

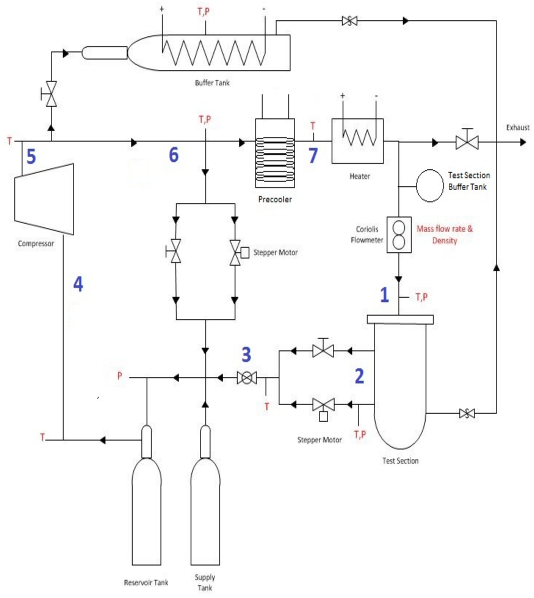

Figure 1 Schematic diagram of test facility at UW-Madison

A description of the conditions typically viewed at various points around the loop during a standard experiment can be seen in figure 2. This figure shows a temperature-specific entropy diagram with points labeled with respect to figure 1.

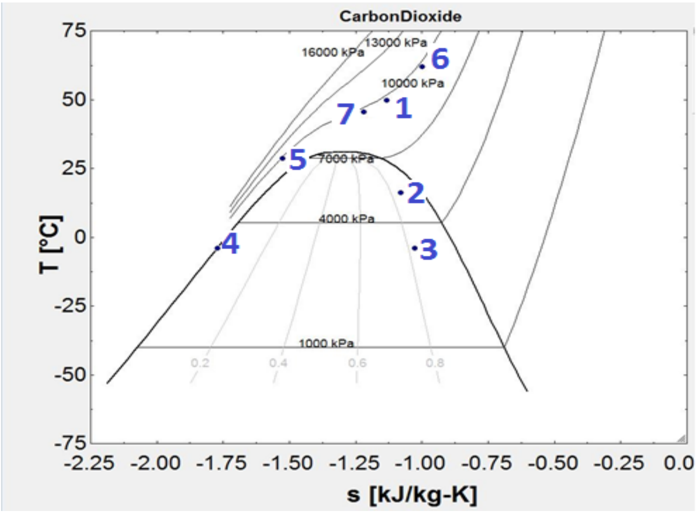

Figure 2 T-S diagram of test facility

The cross sectional view of the test section can be seen in figure 3, which shows the inlet at the top and dual outlet ports from the side. The pressure vessel allows for stagnation conditions to occur immediately following the test geometry. Press fit drill bushings are used to provide the desired outer diameter for the test geometry and the clamp shown holds the seals in place. This method allows for variation in seal geometry by changing the length and diameters of the bushings and allows for the stacking of seals. The length of seals and cavities may be varied along with the diameter of the shaft. For more detailed description about the test facility, please refer to Edlebeck's (Edlebeck 2013) and Wolf's(M. P. Wolf 2014) master thesis.

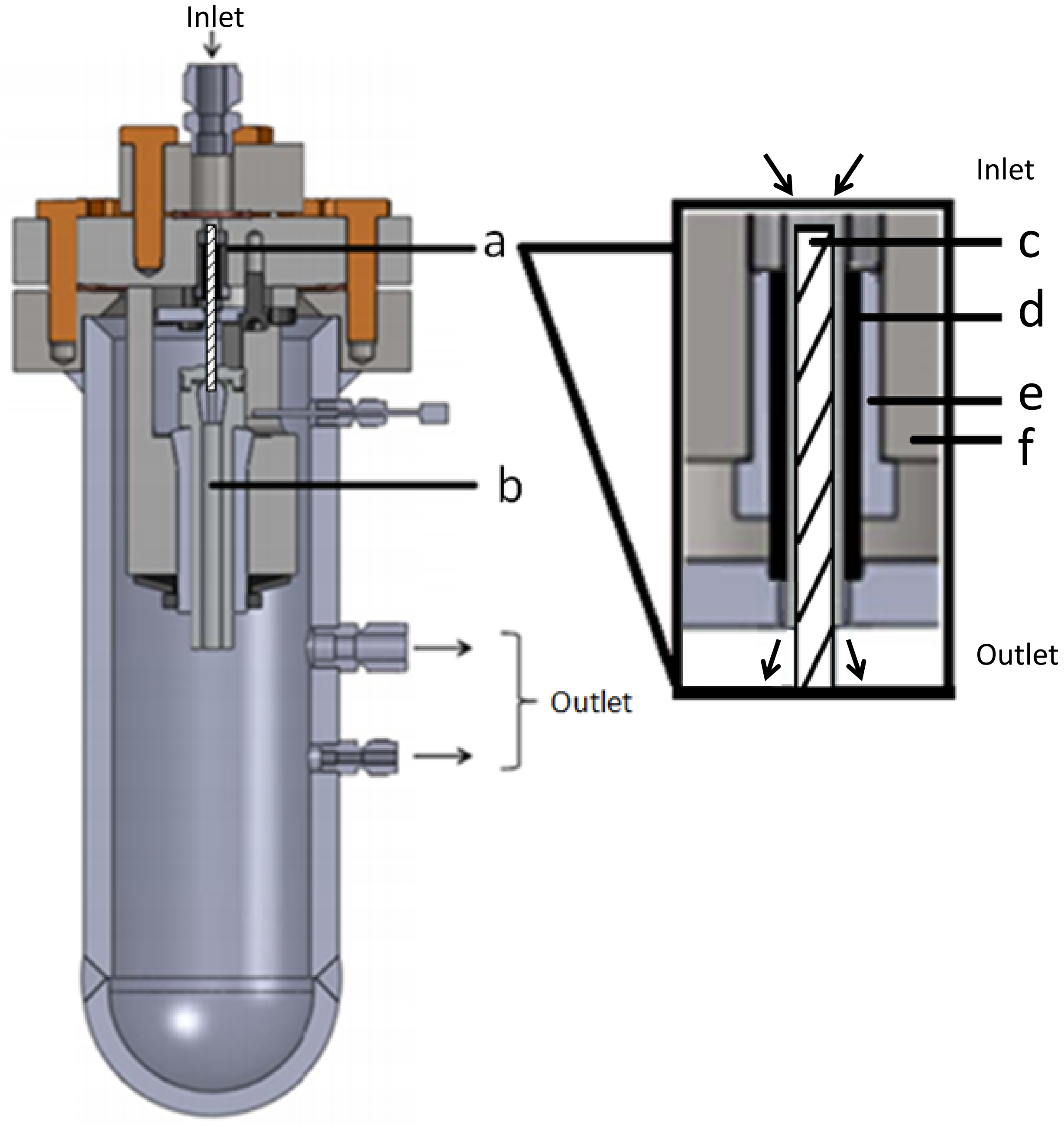

Figure 3 Cross Section of pressure vessel showing a) seal location/configuration, b) collet sub-assembly, c) shaft, d) seal, e) spacer drill bushing, f) test section flange.

NUMERICAL METHODOLOGY

Most commercial CFD software products do not provide access to the source code, which would allow changes to be made to the equations and properties data. As a result it is hard to use commercial CFD codes to simulate supercritical fluid flow if two-phase appears. For example, ANSYS-FLUENT has implemented the REFPROP(Lemmon, Huber, and Mclinden 2007) database into its code to provide real fluid properties. However, it can only be used in supercritical or single phase region. For this reason, the open source CFD code OpenFOAM (Open source Field Operation and Manipulation) has been used in this research in order to handle the supercritical and two-phase simultaneously.

The default OpenFOAM solver for steady-state compressible flow is designed for use with the ideal gas model. However, as supercritical fluid flow is modeled, it is necessary to use a real fluid model. Consequently, the solver has been modified to use the real fluid property data for CO_2, which is provided by an external property code. An interface has been developed to link this external property code with OpenFOAM. Additionally, due to the possible appearance of two-phase, the modified solver uses pressure and enthalpy as primitives for property calculations in order to allow the homogeneous equilibrium model (HEM) to be used within the two-phase dome.

The *rhoSimplecFoam* solver in OpenFOAM is used as the prototype for the modified solver. This solver uses the SIMPLEC(Van Doormaal and Raithby 1984) algorithm to solve the Navier-Stokes equation for steady-state compressible flow. The SIMPLEC algorithm is a permutation of the SIMPLE(Patankar 1980) algorithm with better stability and robustness for some applications.

Initially, the REFPROP(Lemmon, Huber, and Mclinden 2007) database, which is the standard properties code provided by NIST, was used to provide CO_2 properties for OpenFOAM code. However, it is difficult to solve this type of simulation quickly using REFPROP. Alternatively, the fluid properties were calculated using the FIT(Northland Numerics 2012) software library published by Northland Numeric which provides an interpolated representation of the equation of state presented by Span and Wagner(SPAN and WAGNER 1996). The FIT code provides an interpolated representation of properties although the underlying property data are obtained from REFPROP. In this way FIT generates fluid properties much faster than REFPROP within acceptable errors. Figure 4 shows the comparison of FIT and REFPROP property calculation for CO_2. According to Northland Numerics(Northland Numerics 2012), each plot is based on 1e6 points, distributed evenly from 240 K to 1500 K and from 1 kPa to 100 MPa. As we can see, the maximum relative difference is less than 1e-5.

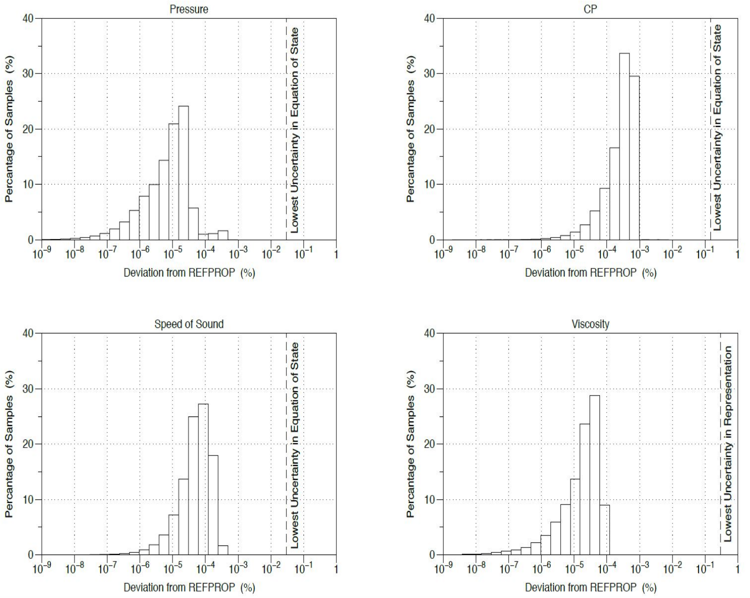

Figure 4 Comparisons of FIT and REFPROP for CO2

RESULTS DISCUSSION

In this part, the results from the experiment and simulation are presented. First, a simple two-tooth labyrinth seal is used to validate numerical results. Then several parametric studies are performed to study the characteristic of S-CO2 flow through labyrinth seal. The parameters selected for the study are the radial clearance, cavity width, cavity depth, and number of teeth. Some parametric studies are presented with both the experimental and simulation data. However, due to limitation of the test facility, some parametric studies are only discussed with the simulation data.

Figure 5 shows the schematic diagram of a two-tooth labyrinth seal. The S-CO_2 enters the seal from the left and leaks out to the right. As we can see in Figure 5, to fully define a see-through labyrinth seal, we need the six parameters in Figure 5 and the number of teeth. However, an inherent correlation $L_{total} = nL_{seal} + (n-1)L_{cavity}$ exists for L_{total}, L_{seal}, L_{cavity} and number of teeth, *n*. Before performing parametric study of different geometrical parameters, it is necessary to verify the numerical code first. Experiments of a two-tooth labyrinth seal were conducted first to provide validation data. The dimension of this two-tooth labyrinth seal are presented in table I.

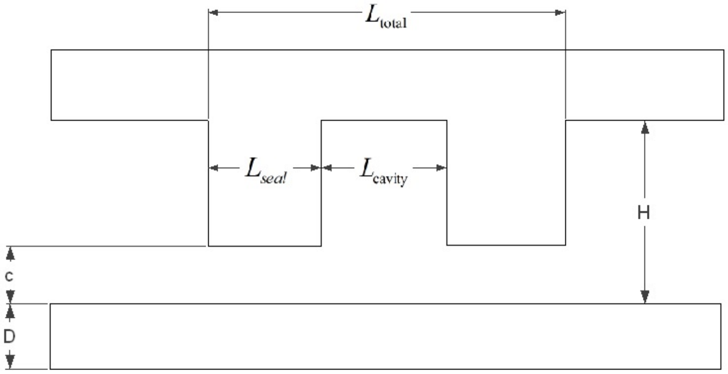

Figure 5 Schematic of a two teeth labyrinth seal

Table I Dimension of two-teeth labyrinth seal

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

Two sets of upstream conditions were tested in the experiment, they are (10 *MPa*, 325 kg/m^3) and (10 *MPa*, 475 kg/m^3), however, only one set of data is presented in Figure 6. The other set of data shows similar agreement. In Figure 6, PR represents the pressure ratio(ratio of downstream to upstream pressure), DC represents the discharge coefficient defined from isentropic discharge model(Klein and Nellis 2012), IS represents the data from isentropic discharge model, EXP represents the data from experimental measurement, OF represents the data from OpenFOAM simulation. It is interesting to note that the DC remains constant for higher PR's, increases over a certain range of PR and stays constant below the choked PR. The reason for this increase in DC over a range of PR is due to the fact that the isentropic discharge model and the real flow choke at different PR's. In reality, the mass flow rate continues to increase even after the 1-D isentropic model chokes and hence, the DC increases till the real flow chokes and stays constant after that. Figure 7 shows the trajectory line of discharge for the data in Figure 6. As we can see, after the downstream condition is inside the two-phase dome, two-phase starts to appear. That is the reason we implemented HEM to handle two-phase.

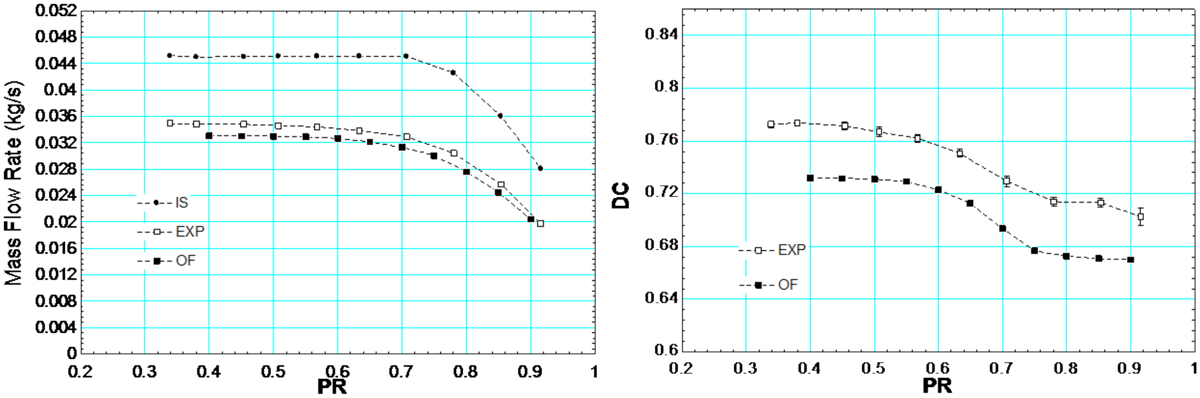

Figure 6 Two teeth labyrinth seal experiment and simulation comparison (10 MPa, 475 kg/m3)

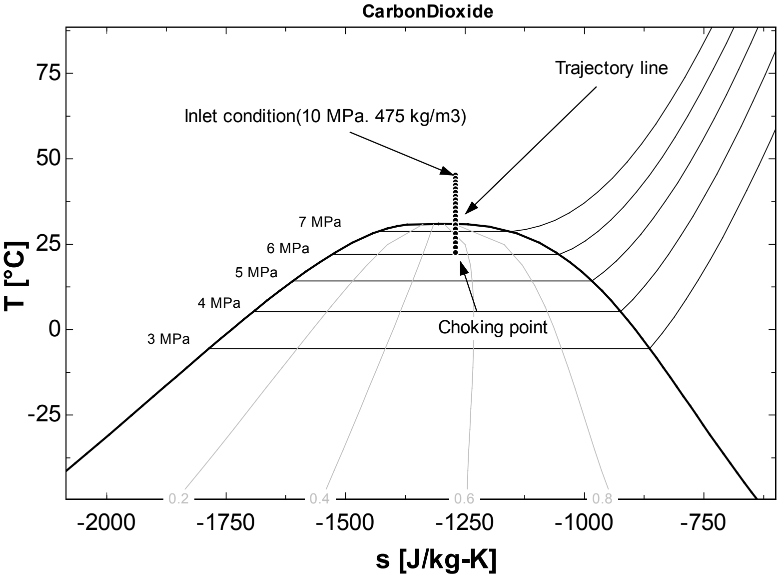

Figure 7 Trajectory line of discharge

After the numerical method is validated with experimental measurement, parametric study was performed to investigate the geometrical influence on the leakage flow through labyrinth seals. In this research, four geometrical parameters are chosen to study their influences on the leakage rate. They are the radial clearance, cavity length (cavity width), cavity height (cavity depth), and number of teeth. The total length is not chosen, because the total length is usually determined by the available space in a turbomachinery component. The shaft diameter is also fixed for experiment and simulation convenience.

Radial clearance

Three-tooth labyrinth seal is used to investigate the effect of radial clearance on the leakage rate. For this study, the seal width is fixed as 0.424 *mm*, cavity width is fixed as 1.268 *mm*, and cavity height is fixed as 0.79 *mm* for a shaft diameter of 3 *mm*. As can be seen from Figure 8, the leakage rate increases with increase in radial clearance. This is a fairly obvious result as an increase in clearance area allows more fluid to be forced underneath the tooth. It should be noted that the inlet operating condition for all these simulations is fixed at a pressure of 10 *MPa*, and an inlet density of 498 Kg/m^3. The outlet pressure is 5 *MPa* for all the cases. Although the results presented here are for a three-tooth seal, conclusions are valid for any number of teeth and different operating conditions as well.

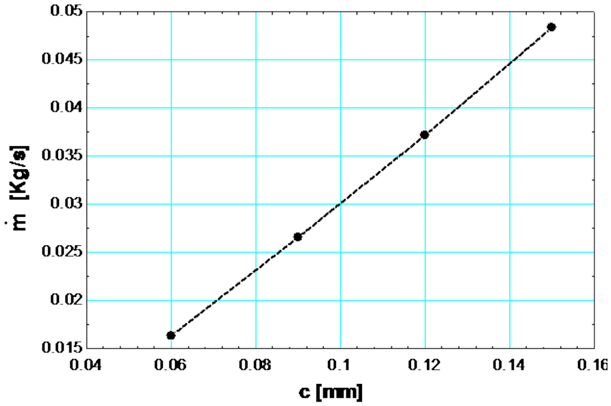

Figure 8 Effect of radial clearance on mass flow rate

Cavity length (Cavity width)

The two-tooth labyrinth seal is used to investigate the effect of cavity length on the leakage. The simulated labyrinth seal has the same parameters as shown in Table I, with a different shaft clearance of 0.09 *mm*. The cavity length is changed to investigate the response of the leakage rate. However, during the change of the cavity length, the total length of the seal is kept constant, which means when increasing cavity length, the seal length (tooth width) is reduced accordingly. In all the following figures, the unit for length and height is 1e-5*m*, and unit for mass flow rate is *kg/s*. In this study the cavity height is fixed to be 88e-5*m*, while the cavity length is sampled evenly between 127e-5*m* to 300e-5*m*. All the data points in Figure 9 have the same inlet condition of (9 *MPa*, 498 kg/m^3) and the same outlet pressure of 5 *MPa*. It has been observed that the leakage rate decreases as the cavity length increase.

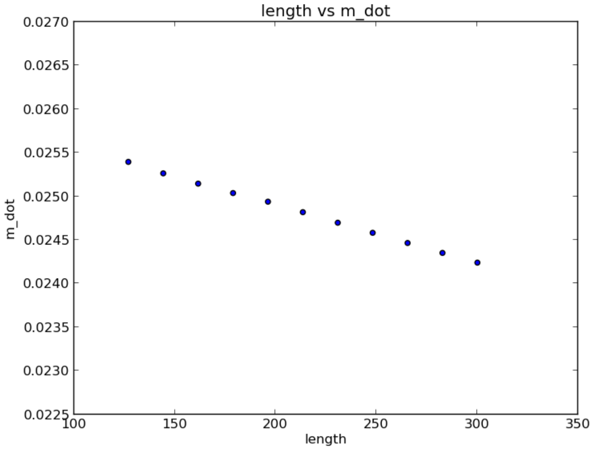

Figure 9 Mass flow rate change with cavity length, cavity height is 88e-5m

After further investigation of the numerical results, we found out that after the main stream enters the cavity, it will spread as a small angle (called expansion angle), and then contract again when it meets the next tooth. During this process, the main stream interacts with the recirculation inside the cavity, and loses part of its kinetic energy. When the main stream contracts at the next tooth, there will be a contraction pressure loss. This pressure loss is proportional to the main stream area change and contributes as a major pressure loss. The expansion angle was assumed to be constant in Hodkinson(Hodkinson and Mech 1939)'s research. However, Suryanarayanan(Suryanarayanan 2009) disagreed with this assumption. The streamline plot from numerical simulation indicated that an increased cavity length results in an increased main stream area change at the next tooth, which produces an increased pressure loss and a decreased leakage. This phenomenon was also observed in Eldin's work(Eldin 2007), even though he used air as fluid.

Cavity height (cavity depth)

In order to inspect the effect of cavity height on the leakage rate, the cavity length is fixed and the cavity height is varied. The data in Figure 10 is based on the simulations of the two-tooth labyrinth seal discussed above. All the data points in Figure 10 also have the same inlet condition of (9 *MPa*, 498 *kg/m*^{3}), and the outlet pressure of 5 MPa. In Figure 10, the cavity length is fixed to be 127e-5*m*, while the cavity height is sampled evenly between 15e-5*m* and 80e-5*m*. Figure 10 concludes that there is an optimum point for the cavity height that results in a minimum leakage rate. This phenomenon is also presented in Eldin(Eldin 2007)'s experiment. He used three five-tooth labyrinth seals with the same cavity length but different cavity heights to demonstrate his finding. Further investigation revealed that this observation can also be explained by the main stream contraction in the cavity. The streamline plot from simulation showed that when the cavity height is too small, it will limit the expansion of the mean stream. If the cavity height is large enough, then the main stream is fully developed. However, there exists a medium value of cavity height that results in a maximum main stream expansion, which leads to a maximum contraction form loss and minimum leakage.

Number of Teeth

In the previous sections, only the cavity length and cavity height are changed to inspect the leakage rate response. In this section, the number of teeth is varied. In order to compare designs for different tooth number, the total length is fixed.

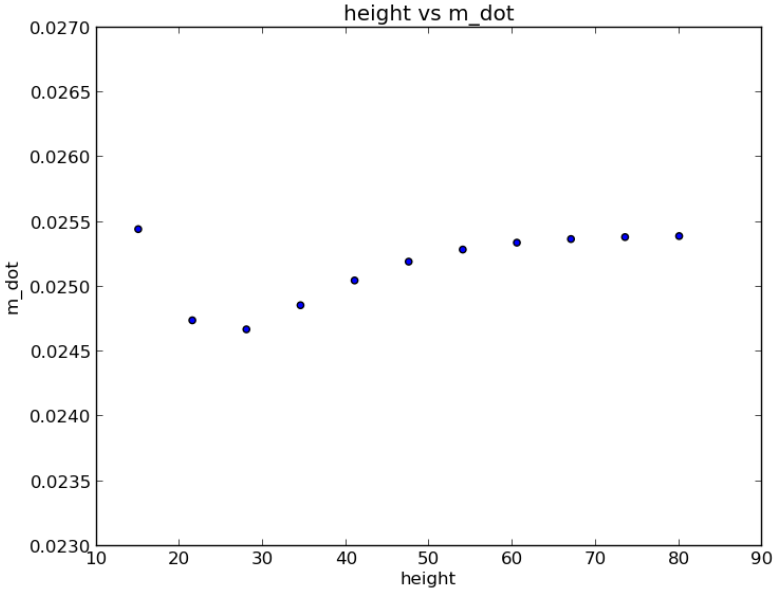

Figure 10 Mass flow rate change with cavity height, cavity length is 127e-5m

From previous section we know that the larger cavity length (cavity depth) leads to lower leakage. This means the minimum tooth width will result in the lowest leakage rate. As a result, in this part, we are using a fixed tooth width for all teeth and assuming this is the minimum tooth width we can have in reality. By inserting more teeth into the seal, the leakage rate initially decreases. However, after a certain number of teeth are inserted, the leakage rate increases. This means that there is an optimum tooth number, which results in a minimum leakage rate. Figure 11 shows the design for different teeth number with the same total length. The designs in Figure 11 have the same total length of 11.43*mm* (0.45”), and the same tooth width of 1.27 *mm* (0.05”). Figure 12 shows the maximum leakage rate for these designs at a fixed upstream condition of (10 MPa, 325 kg/m^3). As we can see in Figure 12, the design with three teeth produces the minimum leakage rate. Moreover, the experimental data of 2, 3, and 5 teeth seals are also provided to validate this finding.

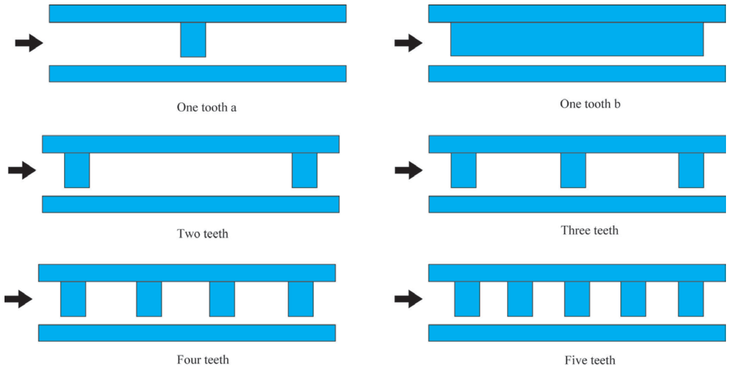

Figure 11 Labyrinth seals with different teeth number

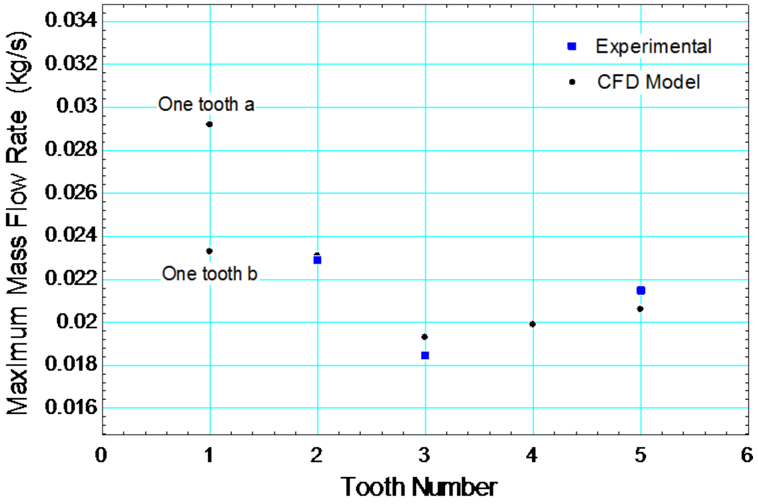

Figure 12 Leakage rate for different teeth number

This observation can be explained as following. From the previous sections, we know that the increasing the cavity length (cavity width) reduces leakage. In this section, as the teeth are inserted into the seal, the cavity length (cavity width) decreases for a fixed seal length. As a result, at a certain point, inserting more teeth can bring more benefits to decrease leakage as cavity length (cavity) is too small. The authors didn't find other papers presenting the similar results.

CONCLUSION

This research studies the S-CO$_2$ flow in the labyrinth seals using both experiment and numerical simulation. The test facility constructed at UW-Madison was used to verify the numerical data and also provide some database which can be used for future research. OpenFOAM was used to perform numerical simulation for this study, with a user-defined property module to provide S-CO$_2$ properties.

Then experimental data and simulation results showed a good agreement with each other for a two-tooth labyrinth seal at two upstream conditions. This comparison validates the numerical methodology for S-

CO2 flow through labyrinth seal geometries. Four different geometry parameters namely, radial clearance, cavity length, cavity height, and tooth number are chosen to inspect their affect on the leakage rate. Increasing the shaft clearance increased the leakage rate, while increasing the cavity length reduced the leakage rate. However for the cavity height, if other parameters are fixed, there is a value of cavity height which results in a minimum leakage. The same holds true for the effect of number of teeth. Some effects were also observed from studies using non-real gas properties like ideal gas. It is believed by the authors that, even though the trend for different parameters' effect on leakage is similar for real gas and non-real gas, the final optimization designs will be quite different for them.

NOMENCLATURE

S-CO_2 = Supercritical Carbon Dioxide

OF = OpenFOAM

EXP=experiment data

CFD=Computational Fluid Dynamic

HEM = Homogeneous Equilibrium Model

UW-Madison = University of Wisconsin-Madison

PR = pressure ratio, Outlet Pressure/ Inlet Pressure

DC = Discharge Coefficient, mass flow rate/ mass flow rate from ideal isentropic model

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