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Flow characterization of steel wool for use in high-temperature actuators

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Abstract

Solid oxide electrolyzer cells powered by renewable energy have the potential to generate green hydrogen without the need for catalysts containing rare and expensive materials as needed in other types of electrolyzers. To accomplish this though, stacks of hundreds of plates must operate at high temperatures, often in the range of 600°C - 800°C. In these harsh conditions, providing a constant preload force to the stacks is crucial to maintaining electrical continuity within the stack and preventing electrically insulating seals between layers from leaking or being damaged. Previously, the authors of this abstract have proposed and conducted initial viability testing on the concept of applying this preloading with a variable-bypass piston[1]. As this concept uses steel wool as a porous seal material, modelling the flow of gas through compressed steel wool will be necessary to enable deterministic design of future variable-bypass pistons to be used in preloading applications. This paper describes the design of a test setup to allow for the collection of data usable for characterization of steel wool as a porous media. Initial results indicate that deriving a deterministic model from the data collected is feasible, and it is proposed that Darcy's Law be used as the basis of this model.

Actuator, flow

1. Background and Motivation

For a successful clean energy transition, establishing the capacity for production of green hydrogen, which is produced without the use of fossil fuels, is necessary.[2] Amongst the types of hydrogen electrolyzers in existence, solid-oxide electrolyzer cells (SOECs) are unique in their potential to operate cost effectively without requiring the use of components incorporating expensive and unsustainable rare-earth metals. To achieve this, they require high internal operating temperatures for their ceramic electrolytes to function, typically in the range of 600°C-800°C. When coupled with processes that produce large amounts of waste heat, such as concrete production, metal smelting, and nuclear power generation, SOECs can operate at high efficiency relative to other electrolyzer types. However, operating in this high temperature regime also imposes significant difficulties in the mechanical design of components, chief of which is creep due to prolonged high temperature exposure. This is a particular issue in the case of solid oxide electrolyzers, where a preload on the order of five kilonewtons is necessary to maintain sealing and electrical continuity in a large cell stack.

2. Use of Steel Wool in Piston Preloading Mechanism

Most preloading methods are ill-suited for use in high-temperature applications such as SOEC systems due to the effects of creep. Those that are, such as dead weight preloading, ceramic springs, and transferring force from outside the hot zone via ceramic rods, are less than ideal due to either high costs or cumbersome form factors. As an alternative, the authors of this paper have previously proposed a variable-bypass piston to be used as a preloading mechanism[1]. This system relies on existing flush or process gas flowing through porous piston seals and generating a pressure differential and ergo preloading force. Due to the compact nature of this design, integration into SOEC stack architectures could allow for a highly space-efficient overall assembly, as well as alternate mounting orientations. (Fig. 1)

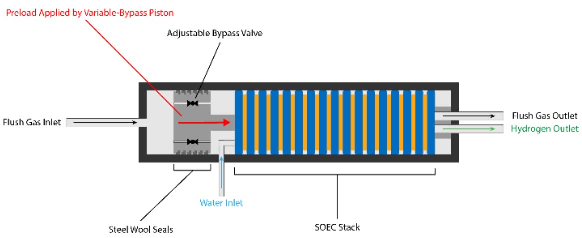

Figure 1. Diagram of Variable-Bypass Piston Preloading SOEC Stack

The properties of steel wool as a high-cycle compression spring [3] also ensures long seal lifespan and concentricity of the piston within the cylinder as a result of elastic averaging. In comparison to other porous media such as graphite or metallic foam, steel wool is able to survive these high temperatures and is creep resistant when lightly stressed.

2.1. Concept Validation & Seal Geometry Evaluation

As a proof of concept for the variable-bypass piston, a tie-rod air cylinder with a bore of 4.5 inches (~115 mm) was modified to allow testing of various piston and seal geometries. The original machined aluminum piston with elastomeric seals was replaced by a new piston fabricated from a combination of machined aluminum and FDM 3D-Printed plastic parts compatible with steel wool seals (Fig. 2).

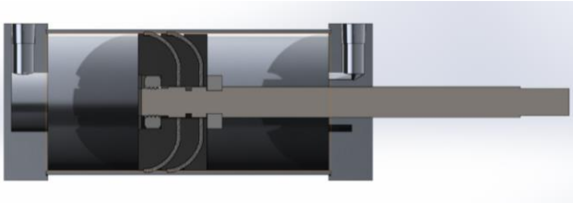

Figure 2. Cross-sectional view of modified tie-rod air cylinder used for seal testing

With this air cylinder, multiple seal and piston geometries were evaluated. Force output of the cylinder was measured with a load cell as a function of gas flow rate, which was controlled with a mass flow controller fed from a standard shop air supply. Performance varied significantly between the seal types tested, with a felted wool seal and conventional ring-seal (wrapped) geometry found to offer the best results (Fig. 4).

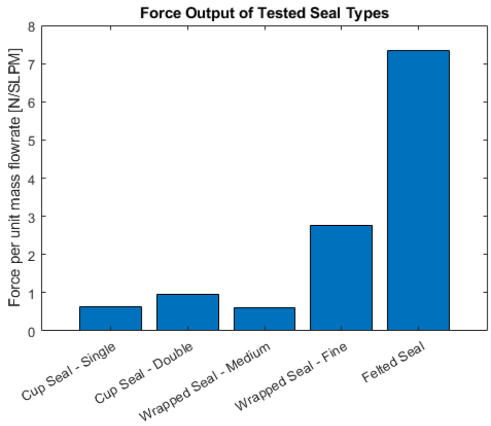

Figure 4. Peak force per unit mass flowrate of tested seal types

In addition to the aforementioned testing of multiple seal geometry types, the conventional wrapped seal geometry was tested with multiple levels of seal compression. This testing revealed that performance varied drastically as a function of seal compression (Fig. 5).

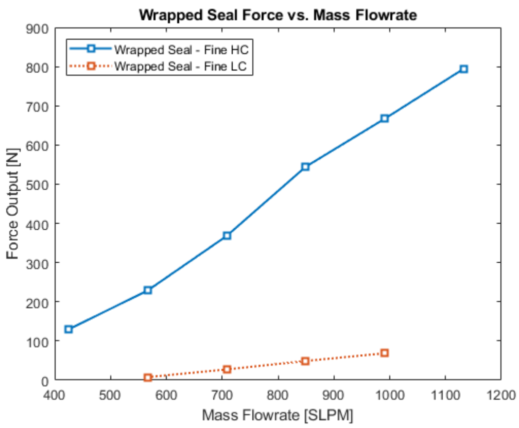

Figure 5. Force output versus mass flowrate for low and high compression versions of wrapped seal

Given this finding, it was determined that establishing a relationship between the compression of steel wool seals and their resistance to flow was necessary to continue development of the variable-bypass piston concept proposed by the authors[1].

3. Steel Wool Flow Characterization

To establish this relationship between compression and resistance to flow, it became necessary to design a test setup which would allow for collection of empirical data and subsequently flow characterization of the steel wool gasket material.

3.1. Flow Characterization Test Assembly

For experimental flow characterization, the functional requirements for the test assembly were that it must be able to control air flow rate, repeatably set the compression of the steel wool test sample, and measure the pressure differential across the steel wool created by the resistance to flow. To allow for rapid and low-cost fabrication, the test assembly was built around a machined polycarbonate tube, with all other parts manufactured via FDM 3D-printing, laser cutting, or derived from COTS parts (Fig. 6).

Figure 6. Flow characterization test assembly

Control of air flow was handled by an external mass flow controller, which itself was fed using filtered shop air at a constant pressure set with a precision regulator. After leaving the mass flow controller, air was fed into one end of the test assembly where the pressure was monitored with a COTS pressure transducer. The air was then forced fo flow under the vertically sliding gate at the center of the test assembly and ergo through the compressed steel wool test sample. Pressure was also monitored downstream of the gate to allow the pressure differential across the steel wool to be measured (Fig. 7).

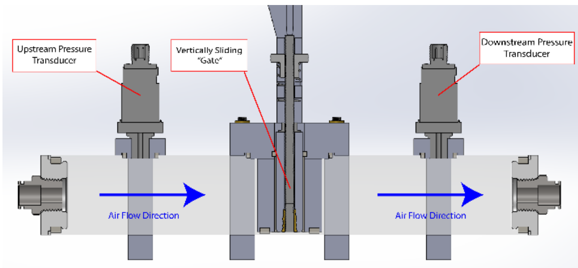

Figure 7. Cross-sectional view of flow characterization test assembly

At the base of the gate assembly, the steel wool test sample is retained by two tabs which are themselves held in place by M2.5 machine screws. This design choice was made to allow samples of varying thicknesses to be retained without the need to change parts. The steel wool test sample is compressed between the gate and the wall of the polycarbonate tube, emulating the geometry of a simple wrapped seal compressed between a piston and cylinder wall (Fig. 8). All potential flow paths around the gate other than directly under it were sealed with laser cut polyethylene foam to force air flow through the compressed steel wool test sample.

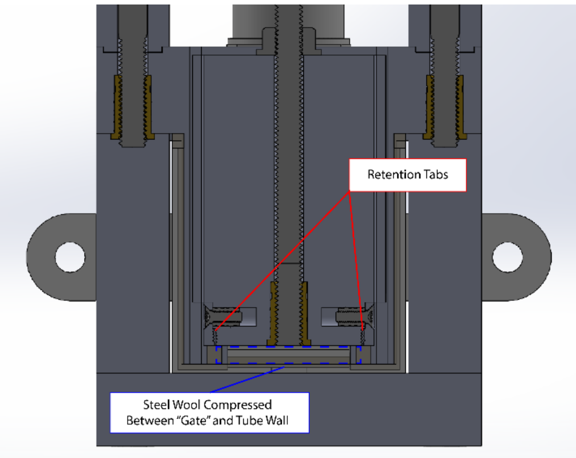

Figure 8. Sliding gate sectional view

The height of the sliding gate and therefore the compression of the steel wool sample was set by a spring-preloaded thumbscrew on a threaded rod which was itself fixed to the gate using a heat-set insert and jam nut. The displacement of the gate was measured using a digital dial indicator mounted integrally to the test setup (Fig. 9).

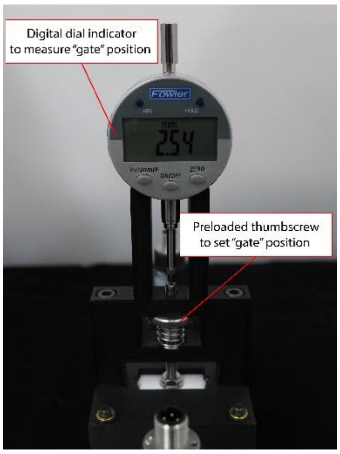

Figure 9. Cross-sectional view of flow characterization test assembly

With the combination of the 1mm pitch threaded rod and the digital dial indicator, repeatable positioning of the gate within the dial indicator resolution of 0.01mm was possible.

3.2. Testing Methodology

Prior to disassembly, the gate was advanced to be in contact with the bottom face of the tube and the absolute zero value of the digital dial indicator was set here. With the displacement value for 100% compression now saved, the sliding gate was removed from the test assembly. Samples 0.5 inches (12.7 mm) wide and 1.5 inches (38.1 mm) long were cut from a spool of commercially available fine steel wool and fixed to the base of the sliding gate using the aforementioned retention tabs (Fig. 10).

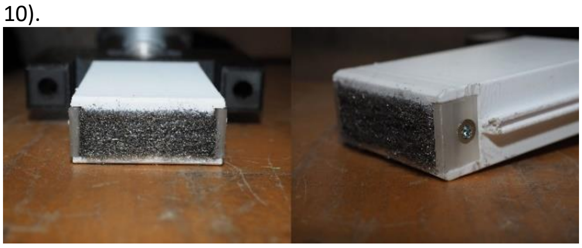

Figure 10. Steel wool test sample fixed in sliding gate

In addition to the samples in their original form as cut from the spool of steel wool, an additional set of samples were needle felted. Needle felting is a process in which barbed needles are passed through a material to entangle fibers. In this case, the process was performed by hand, but automated needle felting is a process used in commercial steel wool manufacturing[4,5]. After the sample was fixed in place, the sliding gate was inserted into the corresponding slot in the test assembly. The sliding gate was then advanced downwards using the preloaded thumbscrew until the steel wool sample made contact with the bottom face of the polycarbonate tube. The point at which the test sample contacted the bottom face of the tube was determined by monitoring continuity of a circuit that was closed when the test sample contacted copper tape fixed to the inside of the tube (Fig. 11).

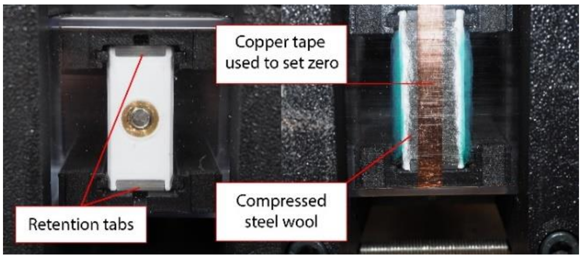

Figure 11. Bottom view of sliding gate and steel wool test sample under compression

After initial contact was made with each sample, airflow was initiated from the mass flow controller at a rate of 15 SLPM and a pressure input to the flow controller of 1 bar gauge pressure. The pressure differential was logged for approximately 10 seconds at this initial position, then the gate was moved downwards in increments of 1mm with the steady-state pressure differential logged at each position. This process was continued until the gate reached the absolute zero value which corresponded to 100% compression.

4. Results and Analysis

With the logged steady-state pressure differential from each position, mean steady-state pressure values were calculated. Plotting the pressure differential as a function of percent compression of the sample allows for the resistance of flow relative to compression to be visualized (Fig. 12).

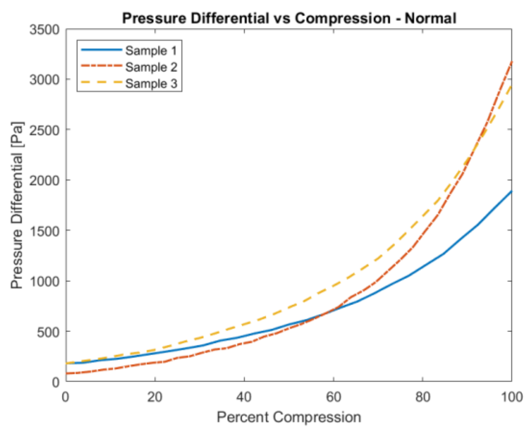

Figure 12. Differential pressure versus compression for normal steel wool

For the three samples of normal wool tested, the induced pressure differential increased exponentially with respect to percent compression of the sample. However, the slope of this curve varies by a significant amount between the three samples tested, with the greatest differences occurring between 40% and 100% compression. Differential pressure as a function of percent compression was similarly plotted for the felted wool samples (Fig. 13).

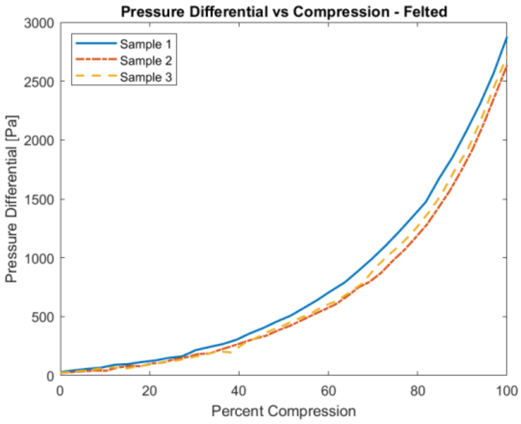

Figure 13. Differential pressure versus compression for felted steel wool

The three felted wool samples all exhibited an exponential relationship between pressure differential and compression similar to that present in the non-felted samples. However, in comparison to the non-felted samples, the pressure-compression curves for the three felted wool samples were much more consistent across the entire compression range. Below 30% compression, the values for the three samples were nearly identical. Peak pressure differential values at maximum compression were similar for both the felted and non-felted test samples.

The more consistent performance of the felted samples is likely an indication that less deformation is being induced by airflow and the felting process allows these samples to maintain integrity at higher pressure differentials. This matches with findings from earlier proof of concept testing using the modified tie-rod air cylinders, where felted seals yielded the best performance and maintained integrity over multiple cycles.

5. Summary & Conclusions

Based on initial testing, the concept of a variable-bypass piston with steel wool seals was validated in its ability to repeatably modulate force output as a function of gas flow rate. To allow for deterministic design of high-temperature actuators using this design concept, it was determined that deriving a relationship between type of steel wool, compression, and resistance to flow was necessary. A test setup to allow data collection necessary for the establishment of this relationship was fabricated, and initial testing with multiple steel wool samples yielded results indicating .

The initial results acquired using the steel wool yielded an exponential relationship between induced pressure differential, or resistance to flow, and compression. For the felted steel wool samples in particular, the pressure differential-compression was very consistent between samples, indicating that developing a model of these seals will allow for deterministic design.

6. Future work

Testing a larger number of samples to establish statistical significance will be necessary to establish a reliable model for resistance to flow as a function of compression. Testing different types of steel wool, including fiber diameter, orientation, and manufacturing method will also be necessary to allow for a wider range of design options. Finally, the model itself will need to be developed based on this test data and the accuracy of its output verified and referenced against test data from an actuator utilizing the variable-bypass piston concept.

6.1. Darcy Porous Media Flow

For the purposes of deterministic design, deriving a relationship between compression, wool type, and resistance to flow is necessary. On the basis of considering steel wool seals as a porous media, it was decided to use Darcy Porous Media Flow equations, originally proposed for subterranean water flow by Henry Darcy[6] as the base for this modeling. With additional data, a generalized form of Darcy's Law (Eq. 1) can be adapted by substituting the constant characterizing the porous media, *k*, for a variable which varies as a function of compression.

$$v = -\frac{k}{\mu}\nabla p$$

Equation 1. Darcy's Law generalized equation[8]

With known values for vector fluid velocity, *v*, derived from flow rate, and fluid dynamic viscosity, μ, a function of temperature[7], the pressure gradient, ∇p, will allow for force output to be calculated based on seal and piston geometry.

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