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A CRYOGENIC COUETTE VISCOMETER TO
MEASURE DISSIPATION AND HEAT TRANSFER
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ABSTRACT

Viscous dissipation and the convection heat transfer coefficient are two key flow parameters that control the operation of twin-screw solidifying extruders. This type of extruder is used to produce hydrogenic pellets that fuel fusion energy machines like the ITER device. This paper discusses a Cryogenic Couette Viscometer (CCV) that is used to measure the viscous dissipation and convective heat transfer coefficient associated with the solidification of cryogenic fluids. Preliminary viscous dissipation measurements of solidifying nitrogen are presented and examined. Modifications to the apparatus are proposed that will allow the measurement of the wall-to-fluid convective heat transfer coefficient and improve the measurement of viscous dissipation.

KEYWORDS: Cryogen properties, Viscous dissipation, Shear, Couette Viscometer

INTRODUCTION

Fusion energy machines like the ITER device require a continuous supply of solidified hydrogenic fuel pellets for sustained operation [1]. These fuel pellets are created by an extruder that solidifies gaseous fuel in order to generate a solid rod that is cut into 3-6 mm segments and fed to a pellet injector. Although there are a variety of extrusion strategies that can be considered, Andraschko [2] showed that the twin-screw extruder is the most promising design for meeting the demands of ITER. A 1/5 scale prototype twin-screw extruder is being developed at Oak Ridge National Laboratory as part of the ITER project [1].

A numerical model of the prototype extruder has been developed [3]. The model has been used to carry out a sensitivity study that showed that the magnitude of the viscous dissipation and the wall-to-fluid convective heat transfer coefficient are the two dominant
parameters affecting extruder performance. Viscous dissipation and the heat transfer coefficient are rheological characteristics associated with the precession of the cryogen as it is solidified within the complex intermeshing screw geometry of the extruder. Prior to the work of Meitner [4], little research existed related to the viscous dissipation associated with continuously sheared frozen cryogens.

Couette Viscometers (CVs) have been used for several decades to measure the rheological properties of fluids in order to understand and design screw extruders [5]. Within a CV, a Couette flow is created when two coaxial cylinders are rotated relative to one another, as shown in the inset of Figure 1. It is customary to call the inner rotating cylinder the bob and the outer stationary cylinder the cup. The viscous dissipation in the fluid can be inferred based on measurement of the induced torque, $M$, and rotational speed, $\omega$, associated with the bob. The fluid shown in Figure 1 is undergoing solidification and therefore there exists both a solid layer (closest to the cup which is being cooled) and a liquid layer (closest to the bob).

A Cryogenic Couette Viscometer (CCV) has been developed to measure the viscous dissipation associated with frozen cryogens [4]. The design and operation of this apparatus is discussed and initial nitrogen viscous dissipation measurements are presented and examined. Modifications to the apparatus are proposed that will allow the measurement of the wall-to-fluid convective heat transfer coefficient and improve the measurement of viscous dissipation.

APPARATUS DESIGN AND OPERATION

Figure 1 shows a rendering of the components associated with the CCV. Fluid flows into the cup via an annular gap that exists between the driveshaft and the driveshaft housing. The cup has an inner diameter of 86.2 mm and a height of 102.4 mm. The bob has an outer diameter of 76.2 mm and a length of 100 mm. The annular space between the cup and bob has a thickness of 5 mm and an approximate volume of 127.5 cm$^3$. A nichrome heating element with a room temperature resistance of 68.6 $\Omega$ is wrapped around the base of the cup. A Cryomech GB-04 Gifford McMahon cryocooler is thermally connected to the cup through a heat-flow calibrated bus bar that includes a flexible thermal strap to prevent any of the torque applied by the bob from being transmitted to the cryocooler. Each of the thermal interfaces is made using a 0.25 mm thick indium foil. Cernox® 1070-SD resistance temperature devices (RTDs) are attached at the four measurement locations indicated in Figure 2 using Apiezon N® grease and spring mounts. Two of these sensors are installed in order to determine the temperature of the cup while the remaining two sensors measure the temperature difference across the bus bar. A 2.5 mm thick copper radiation shield is connected to the 1st stage of the cryocooler and is insulated by 25 layers of MLI (not shown in the figure) from the surrounding inner wall of the liquid nitrogen jacketed dewar.

External to the cryostat, a ¼ horsepower DC gear motor drives a hollow drive shaft made of 304 stainless steel that is connected to the bob. A copper shear pin connects the motor to the drive shaft. The shear pin is designed to fail when the torque exceeds 100 N-m in order to protect the shaft. A magnetic proximity switch measures the rotational speed of the drive shaft. Strain gages attached to an aluminum bar that prevents rotational motion of the motor housing measure the torque on the drive shaft; the strain bar is calibrated prior to each test using weights placed on a lever arm. The drive shaft is sealed to the housing with a dynamic o-ring. A high-pressure gas cylinder filled with 99.999 % pure nitrogen is connected to a room temperature reservoir with a volume of 21.2 liters.
The pressure within the reservoir is measured in order to determine the mass of fluid that leaves the reservoir and is provided to the CCV. The RTDs are read with a Lakeshore Model 208 Temperature Monitor.

A series of measurements begins with the reservoir nominally charged to 650 kPa, the entire apparatus at room temperature, and a vacuum of $5 \times 10^{-5}$ torr in both the cryostat and cup. The strain bar is calibrated. The valve connecting the fill line to the vacuum pump is closed and the valve connecting the fill line to the reservoir is opened, allowing nitrogen gas to flow into the cup. The cryocooler is activated and the apparatus is allowed to cool. As the apparatus cools, the nitrogen in the cup will increase in density, causing nitrogen to flow from the reservoir to the cup. The reservoir volume was sized so that the pressure within the reservoir is reduced to approximately 150 Pa when the annulus is completely full of solid nitrogen. The valve connecting the fill line to the reservoir is left open during the measurements to ensure that the annulus is completely filled and allow for minor changes in volume from thermal contraction of the solid nitrogen at sub-cooled cup temperatures.

Once the cup is cooled below 65 K (slightly above the nitrogen triple point temperature of 63.151 K [6]), the apparatus is ready for measurements. A LabView virtual instrument is used to record the strain gauge and applied nichrome heater voltages with a frequency of 500 Hz. The mean values of these voltages is recorded every 0.5 seconds, which corresponds to the frequency of the temperature measurements provided by the temperature monitor. The nichrome heating element is activated and provides sufficient heat to balance the cryocooler cooling power and achieve a steady state operating condition. The heating element is used to calibrate the bus bar (i.e., measure the temperature difference as a function of applied heater power) at 0.5 K temperature increments (as determined by the RTD located at the top of the cup) from 63.5-57.5 K. This set of measurements serves as a baseline for the apparatus when no viscous dissipation is occurring (the bob is not rotating). After the bus bar is calibrated, the cup is heated above the triple point temperature, allowing the solid nitrogen to melt. The motor is started and the desired rotational speed is set.

With the motor running and the cup below the triple point temperature, significant viscous dissipation begins to occur when the freeze front contacts the rotating bob. The
electrical power provided to the nichrome heating element is adjusted in order to balance the cryocooler load and viscous dissipation at the same 0.5 K temperature increments previously used to calibrate the bus bar. These tests are repeated at various motor speeds. The measurements that result from these tests are torque and heater power for various values of temperature and motor speed. The torque data is time resolved in order to identify interesting transient behavior.

**DATA AND ANALYSIS**

Figure 2 shows the measured torque as a function of time at various temperatures for the data collected at a shaft speed of 0.4 RPM. There is a clear cyclic torque fluctuation as large as 10 N-m associated with the 63.0 K, 60.5 K, and 59.0 K measurements. The period between the spikes (150 s) corresponds directly to the rotational speed of the shaft and it is likely that the cause of the torque spike is related to eccentricity or bending of the drive shaft.

Figure 3 shows the measured torque as a function of time at various temperatures for the 0.76 RPM shaft speed. The 63.5 K and 63.0 K data are similar to the data collected at 0.4 RPM. The 63.5 K data exhibits an oscillation of approximately 10 N-m that is associated with the mechanical sources of friction. The 63.0 K data also exhibits a once per revolution oscillation with a slightly lower average torque than was observed at the same temperature with 0.4 RPM.

The behavior observed at a temperature 62.5 K and lower temperatures is remarkably different. At 62.5 K, a very large oscillation in the torque occurs with a period of approximately 174 s, which is significantly larger than the cycle time. At 60.5 K, the data also exhibits oscillations in the torque that are substantially larger than the mechanical oscillations observed in the 0.4 RPM data set.

One possible explanation for the behavior observed in the 62.5 K data set is the motion of the freeze front within the annular gap. The freeze front moves from the wall of the cup (where the cooling is applied) towards the wall of the bob. The magnitude of the viscous dissipation increases substantially as the freeze front contacts the bob and the solid nitrogen is sheared. Depending on the relative rate of dissipation and cooling, this situation may not be stable. If the gap is sufficiently small or the freeze front touches the bob then the viscous dissipation will increase and this may cause the freeze front to melt away from the wall. As the gap increases, the viscous dissipation drops and eventually the freeze front moves back towards the wall. This phenomenon is manifested as a series of regularly spaced (in time) torque spikes at a period that is unrelated to the rotational speed of the device, as seen in Figure 3. Instead, the time between the torque spikes is related to the time required for the freeze front to progress across the gap.

The time required for the freeze front to move back and forth within the gap can be estimated, approximately, using a scaling analysis. The cooling provided at the freeze front by conduction from the cooled cup surface is approximately:

\[
q_{\text{cond}} = k_s 2 \pi \bar{r} L \left( \frac{T_{\text{tp}} - T_{\text{cup}}}{r_{\text{cup}} - r_{\text{bob}}} \right) / 2
\]

where \( \bar{r} \) is the average radius in the annular space, \( k_s \) is the conductivity of the solid, \( T_{\text{tp}} \) is the triple point temperature (the temperature of the freeze front), and \( T_{\text{cup}} \) is the measured cup temperature. The factor of two appears in the denominator of equation (1) based on the...
approximation that the freeze front is, on average, in the center of the gap. The rate of heat conduction balances the rate of solid formation that causes the freeze front to propagate:

$$\frac{dU_{\text{latent}}}{dt} = 2 \pi r L \rho_s \Delta i_{\text{fus}} \frac{d\delta}{dt}.$$  \hspace{1cm} (2)

where $\rho_s$ is the density of solid, $\Delta i_{\text{fus}}$ is the latent heat of fusion, and $d\delta/dt$ is the radial velocity of the freeze front. Balancing conduction with the rate of latent heat release, Eqs. (1) and (2), leads to:

$$k_s 2 \pi r L \frac{(T_p - T_{\text{cup}})}{(r_{\text{cup}} - r_{\text{bob}})/2} = 2 \pi r L \rho_s \Delta i_{\text{fus}} \frac{d\delta}{dt} \implies \frac{d\delta}{dt} = \frac{2k_s (T_p - T_{\text{cup}})}{(r_{\text{cup}} - r_{\text{bob}}) \rho_s \Delta i_{\text{fus}}}.$$ \hspace{1cm} (3)

Equation (3) is used to define a characteristic time based on the time required for the freeze front to move one eighth of the way across the gap:

$$\tau_{\text{char}} = \frac{(r_{\text{cup}} - r_{\text{bob}})^2 \rho_s \Delta i_{\text{fus}}}{16 k_s (T_p - T_{\text{cup}})}.$$ \hspace{1cm} (4)

Figure 4 shows the period predicted by equation (5) and the observed period of the torque oscillations as a function of the cup temperature. Notice that the characteristic time has the correct order of magnitude and varies with temperature in the correct manner.

Figure 5 shows the viscous dissipation, calculated as the product of the time average torque and the speed, as well as the viscous dissipation determined using the bus bar calibration. The dissipation measurements calculated based on the torque measurements are systematically lower than the dissipation determined using the bus bar. However, the results of the two measurement techniques agree quite well.

![FIGURE 2](image-url)
FIGURE 3. 0.76 RPM drive shaft torque over time for various cup temperatures.

FIGURE 4. Comparison of calculated freeze-thaw cycle period $\tau$ from equation (4) with measured periods from the 0.76 RPM data.
FIGURE 5. Steady state viscous dissipation versus cup temperature as determined by torque measurements and bus bar calibration.

PROPOSED APPARATUS MODIFICATIONS

Modifications to the experimental apparatus are envisioned that will improve experimental accuracy and operating range through an increase in available cooling capacity, an increase in the maximum possible drive shaft torque, and measurement of the bob temperature and heat flux. Figure 6 is a computer rendering of these improvements in the proposed 2nd generation of the CCV.

The available cooling capacity must be increased because the current configuration has little available cooling capacity for the 0.76 RPM set of nitrogen measurements. It is therefore likely that the available cooling capacity will be insufficient for similar measurements using neon, deuterium, or hydrogen. To reduce the parasitic heat loads, a new drive shaft will be constructed from titanium alloy to reduce the integrated average thermal conductivity by 50%, increasing the available cooling capacity by 0.6 watts. The titanium alloy has a higher shear stress and will increase the maximum operating torque by 50%. These modifications will also provide the opportunity to reduce the drive shaft eccentricity through improvements in the mechanical design. A second bob and cup with smaller diameters will be constructed. The smaller bob diameter decreases the viscous dissipation and increases the available cooling capacity. Also, because the area of the ends decreases according to the radius squared while the cylindrical outer area decreases by radius, the relative impact of end effects will be reduced significantly.

In order to accurately calculate the heat transfer coefficient for the solidifying flow, it is necessary to measure the temperature of the bob. A liquid mercury filled rotating wire connector will be used to allow the driveshaft to rotate freely without significant additional electrical noise. A cartridge heating element will be integrated with the bob in order to provide a constant and measurable heat flux through the solidifying cryogen. The ratio of the heat flux to the temperature difference will determine the heat transfer coefficient across the annular gap.
CONCLUSIONS

Measurements of the viscous dissipation of solid nitrogen have verified the feasibility of a Cryogenic Couette Viscometer (CCV). Interesting behavior has been observed with the CCV that involves periodic torque fluctuations, likely related to the periodic motion of the freeze front within the annular gap. For measurements of solid neon, deuterium, and hydrogen, it is necessary to increase the available cooling capacity of the system. In order to measure the heat transfer coefficient and the viscous dissipation, it will also be necessary to measure the heat flux and temperature associated with the rotating bob.

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FIGURE 6. Rendering of the 2nd generation Cryogenic Couette Viscometer (CCV).