

Viscosity Measurement of Gaseous and Supercritical Fluids as a Dielectric Medium

Amanda West¹, Jia Wei¹, Alfonso Cruz¹, Farhina Haque², Chanyeop Park², Zhiyang Jin¹, and Lukas Graber¹

(1) School of Electrical and Computer Engineering, Georgia Institute of Technology

(2) Department of Electrical and Computer Engineering, Mississippi State University

awest93@gatech.edu

Abstract—Supercritical fluids (SCFs) are being investigated as a dielectric medium for their low viscosity, high dielectric strength, high heat transfer capability, low cost, and environmental friendliness. This paper introduces a straight-forward, cost-effective, and commercially available sensor to measure SCF viscosity for the characterization of the dielectric medium. Quadratic and cubic fitting between the sensor current output and viscosity of He, H₂, CO₂, SF₆, and N₂ were made in the ambient lab environment. Experimental temperatures range from 19.3°C to 22.0°C and fluid pressure from 0.1 MPa – 1.5 MPa. This manuscript introduces preliminary data for a methodology to correlate SCF viscosity to the output signal of a commercially available sensor. This will enable viscosity measurement of mixtures of dielectric fluids.

I. INTRODUCTION

Recent technological trends towards the integration of renewable energy, the need for higher capacity in power transmission and distribution, as well as the push for the electrification of the transportation sector justify the investigation of DC power grids at both the MV and HV levels. One major challenge to widespread integration of DC power grids is DC fault current protection. Fast, efficient, and reliable circuit breakers are under development to address this challenge. MV and HV switching DC fault currents face a unique encumbrance compared to AC fault current protection. AC circuit breakers are designed to interrupt the fault current during its natural zero-crossing. Whereas in DC power systems, there are no zero-crossings and the fault current keeps rising linearly with the reactance of the system. Thus, DC breakers rely on different technologies to interrupt the fault current including the introduction of hybrid and solid-state resonance circuits, which lead to large oscillations and the introduction of zero-crossings. Additionally, DC circuit breakers must interrupt the fault current faster, particularly for a voltage-source converter-based system, due to the rate of rise of fault current. The challenges of HVDC circuit breakers are outlined in [1]. One implementation is to commutate the fault current from the main mechanical switch path to a parallel connected solid-state breaker. This implementation by Graber *et al.* as a hybrid dc circuit breaker, EDISON, which operates with a contact separation speed of 0.1 mm in 250 μ s (0.4 m/s) and limits the fault current to 8 kA [2]. The EDISON circuit breaker, shown in Fig. 1, uses a fast mechanical switch (FMS) in parallel with the combination of a fault current commutation branch (FC3) in series with a power stack.

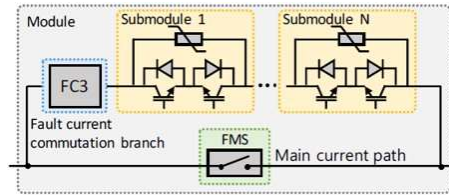


Fig. 1. EDISON Hybrid DC Circuit Breaker Operating Principle [2]

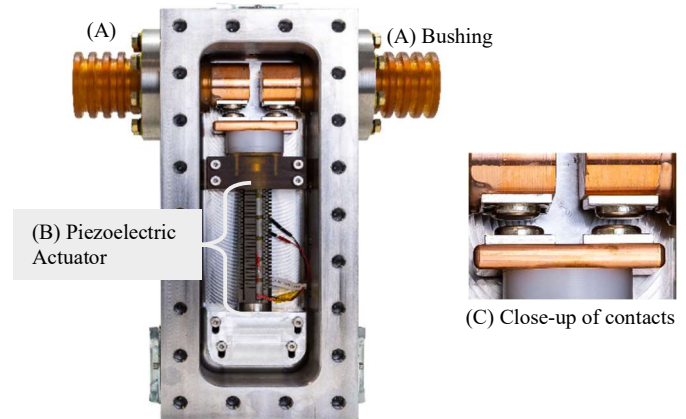


Fig. 2. EDISON Fast Mechanical Switch (FMS): (A) Bushings, (B) piezoelectric actuator, (C) close-up of contacts [2]

The FMS in Fig. 2. includes a piezoelectric actuator with nanometer actuator displacement resolution and 1000 N of contact forces when the switch is fully closed. The contact forces reduce on-state conduction losses and the nominal current rating of the FMS. This actuator outperforms the normally used Thompson coil in controllability, actuation efficiency, mechanical structure, and stiffness. The piezoelectric actuator travel distance is 0.1 mm and requires a high dielectric, low viscosity medium to ensure the FMS withstands the increased voltage during the 250 μ s contact separation. Xu *et al.* demonstrated the feasibility of supercritical CO₂ (sCO₂) fluid in the EDISON circuit breaker based upon its dielectric strength [3]. However, the effect of viscosity on the switching speed of ultra-fast gas insulated switchgear (GIS) has not been adequately studied. This effect can appear as the drag force according to Newton's equation of motion:

$$F_{total} = m \cdot \frac{dv}{dt} = F_{actuator} - F_{drag} \quad (1)$$

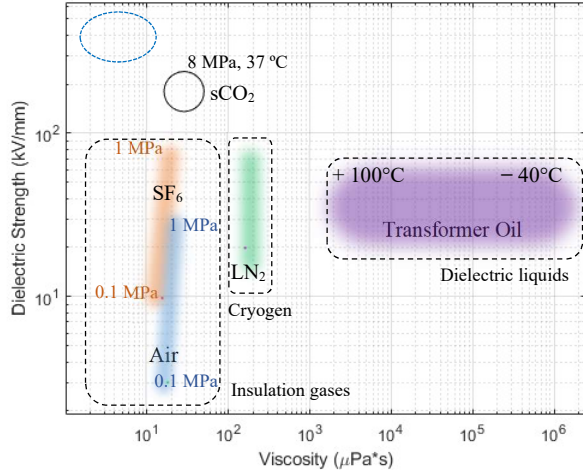


Fig. 3 Dielectric strength of common insulating materials compared to dynamic viscosity [4]–[6]. SF₆ and air in room temperature. Dashed line is the speculated region of sCO₂-CF₃I.

The drag force has two contributing factors: the shape of the moving contact plate and the viscosity of the surrounding fluid. While the geometry is immutable, we can select a medium with low viscosity such as a SCF.

SCFs exist in a state where the temperature and pressure are above the critical point. Exhibiting qualities of liquids and gases, SCFs are studied extensively in multiple disciplines: chemistry, material science, nuclear physics, extraction, and drying. Within the power electronics sector, some investigate SCFs as replacement medium for SF₆ to mitigate harmful environmental effects and achieve higher dielectric strength in GIS. The dielectrics strength of supercritical N₂, CO₂, and CO₂-CF₃I is studied in [7]–[9]. Gaseous and supercritical He has proven to be a viable coolant for high-temperature superconducting (HTS) cables in high voltage direct current (HVDC) transmission systems [10]. However, there are not many studies about the influence of SCF viscosity on the circuit breaking capability of switchgear. When the contact separation distances are less than a millimeter, as in [2], [3], the viscosity may become an important factor in arc breaking speed. The optimal dielectric material for the hybrid DC circuit breaker has a high dielectric strength and low viscosity.

The blue dashed line in Fig. 3, above, represents the impetus of this research. A dielectric medium with high dielectric strength and low viscosity would exist near the blue dashed line. SCF CO₂ has these properties and can be improved by mixing it with other high dielectric materials such as CF₃I. SCF CO₂-CF₃I has a dielectric strength of 350 kV/mm which is higher than air, SF₆, SCF CO₂, LN₂, and transformer oil [4], [5], [8]. However, there are no measurements of SCF CO₂-CF₃I viscosity. To properly compare SCF CO₂-CF₃I to the other insulating materials the viscosity must be investigated.

One hindrance to measuring the viscosity of SCFs is that the viscometers appropriately designed for SCFs are not widely

available commercially. The commercially available viscometers operate in medium with viscosities between 0.2 – 2,000,000 mPa*s and pressures between 0.01 – 1 MPa. The viscosity and pressure of SCF CO₂ at the critical point is 28.4 μPa*s and 7.35 MPa. To our knowledge the viscometers which measure the range of viscosity for SCFs, are custom-built in research groups. A simple, commercially available sensor with a reasonable price should be available.

This paper explores a new approach to measuring the viscosity of SCFs using a commercial sensor, presents preliminary results, and a future research plan. The Trafag 8774 density sensor, which implements the oscillating quartz crystal tuning fork method, was selected for the ease of implementation and reasonable cost.

II. EXPERIMENTAL METHODS

A. Quartz Tuning Fork Measurement Method Theory

The Trafag 8774 sensor operates according to the inverse piezoelectric effect. “The deformation of the tuning fork due to the viscosity of the medium can be determined by the equation of motion of a one-sided fixed, elastic beam [11]. The relative reduction of its resonance frequency $\Delta\omega/\omega_0$ due to the presence of gas is given by the equation of motion of a one-sided fixed, elastic beam:

$$\Delta\omega/\omega_0 = \rho_g t 2\rho_q w c_1 + c_2 \delta t \quad (2)$$

where ρ_g is the gas density, ρ_q is the quartz density including gold electrodes, t the thickness of the wafer plate used, w width of the fork and:

$$\delta = 2\eta\rho_g\omega_0 \quad (3)$$

is the thickness of the whirl surface layer. η is the dynamic temperature-dependent viscosity of the gas, and c_1 as well as c_2 are geometry dependent constants. The first part of Eq. (4) describes the influence of the additive mass of the gas, whereas the second part counts for shear forces arising in the outmost surface layer of the tuning fork. The characteristic relationship of density ρ and frequency shift Δf during sensor operation can be described by:

$$\Delta f = A\rho + B\rho + C \quad (4)$$

where $A = c_1 t 2\rho_q w f_0$ and $B = c_2 2\rho_q w \eta \pi f_0$ are coefficients to be determined and C is an additional offset constant.”

B. Trafag Sensor

The Trafag 8774 SF₆ density sensor in, as shown in Fig. 3, is a commercially available sensor which employs two quartz crystal tuning forks to calculate density and viscosity. One tuning fork is enclosed in vacuum and the other is exposed to the fluid. The temperature is consistent across both sensors, so there is no need for temperature compensation in viscosity calculation [12]. A diagram of this operating principle is shown

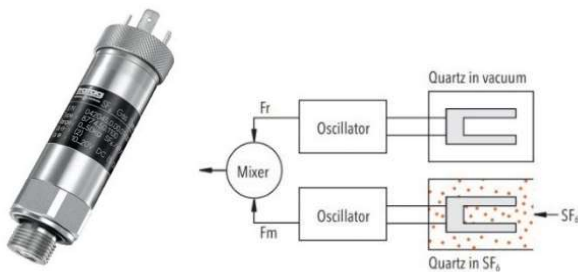


Fig. 3. Trafag 8774 SF₆ density sensor and operating principle

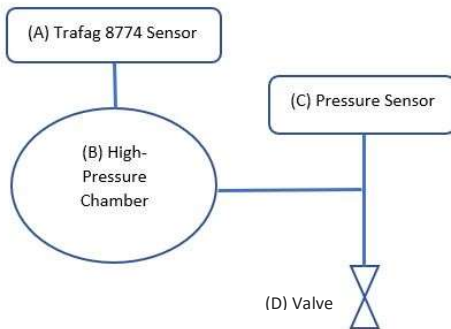


Fig. 4. Viscosity measurement setup: (A) Density sensor, (B) high-pressure fluid optical chamber, (C) pressure sensor. Blue lines: 1/4" stainless steel tubing. (D) Valve: gas inlet and outlet.

in Fig 3. Choudhury *et al.* confirm the feasibility of this sensor for viscosity measurements in GIS systems for SF₆ GIS leak detection [13]. This paper expands the sensor application to measurements of multiple fluid viscosities for dielectric medium characterization in hybrid DC switchgear.

Frequency shifts in the quartz tuning fork were measured when immersed in CF₃I, He, H₂, CO₂, SF₆, and N₂ in the ambient lab environment with temperatures ranging from 19.3°C to 22°C. The Trafag 8774 conditioning circuit compares the immersed tuning fork frequency shift to the tuning fork in vacuum and outputs a current. This current was recorded using the data acquisition setup shown in Fig. 4.

C. Data Acquisition Setup

The power input to the sensor was 17.8 V DC using a MeanWell RT-50C. The data output of the sensor fed through a 500 Ω 1% precision sensor to ground. The voltage was measured across this sensor and acquired by an NI 9229 module within a cDAQ 9185 chassis which was connected to a laptop computer for data processing using LabVIEW 2020.

III. PRELIMINARY RESULTS AND DISCUSSION

The sensor output current consistently increases with increasing pressure as shown in Fig. 5. The rate of increase in sensor output current is proportional to the density of the fluid. Less dense fluids, such as He and H₂ exhibit very small rate of change of sensor output current. Whereas, denser fluids such as SF₆ and CO₂ exhibit larger rates of change. This is a result of

the operating principle of the quartz tuning fork. The less dense fluids perturb the fundamental resonance of the exposed quartz crystal at a slower rate compared to more dense fluids at the similar temperatures and pressures.

To our knowledge, there is no literature which describes the viscosity of pure CF₃I (light blue) in the same pressure range as this work. Duan *et al.* recorded CF₃I viscosity measurements at atmospheric pressure with temperatures ranging from -40.15°C - 179.85°C [14]. Therefore, the sensor output current while measuring CF₃I has no viscosity correlation or reference viscosity. Additionally, the experimental setup contained a small amount of air when transferring the fluid chamber from a vacuum pump to the gas cylinders. However, this small addition should not affect the overall measurement. The air was trapped in a nylon tube with volume of about 3 cm³ and the volume of the measurement chamber was 23.95 cm³. This will be remedied in future work by connecting the gas cylinder, fluid chamber, and vacuum pump in one enclosed system.

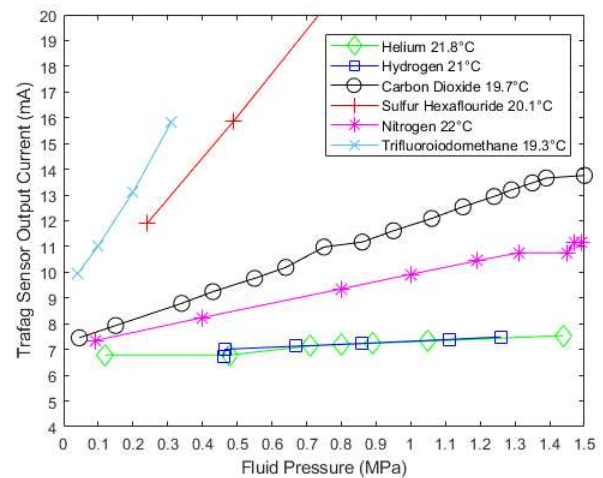


Fig. 5. Sensor current output with fluid pressures between 0.1 - 1.5 MPa (specified range of the sensor).

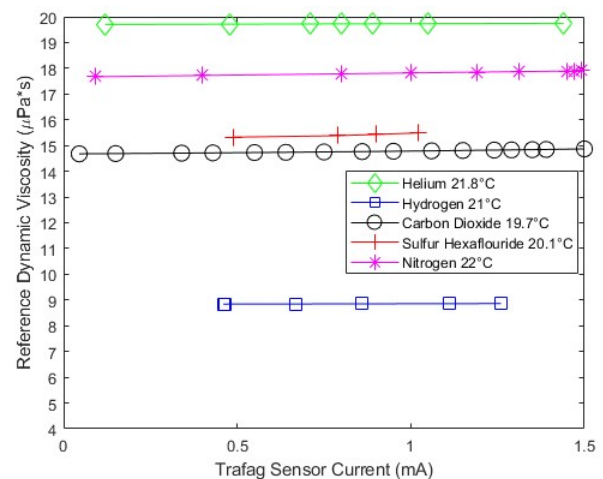


Fig. 6. Sensor current output correlation with reference viscosities over a range of fluid pressures (0.1 - 1.5 MPa).

The measured sensor outputs were correlated with reference viscosities found in [15], [16]. Each fluid has increasing viscosity with increased fluid pressure. This increase is very small, for instance SF₆ viscosity increases from 15.25 $\mu\text{Pa}\cdot\text{s}$ - 15.49 $\mu\text{Pa}\cdot\text{s}$ corresponding with a 0.24 MPa - 1.02 MPa fluid pressure change. The correlation of the sensor output and reference viscosities of each fluid at an isotherm is shown in Fig. 6. and Table 2.

The correlation of the fluid viscosity to the sensor output current follows the correlation of fluid viscosity to pressure at an isotherm. The range of currents corresponds to the density of the fluid. The specific ranges of density and sensor output currents at the experimental pressures (0.1 – 1.5 MPa) and 20°C are listed in Table 1.

TABLE I

Fluid Density and Sensor Output Current Range for Experimental Pressure

Fluid	Density (kg/m ³)	Sensor Output Current (mA)	Δ Sensor Output Current (mA)
He	0.16 – 2.45	6.79 – 7.54	0.75
H ₂	0.08 – 1.23	6.71 – 7.49	0.778
N ₂	1.15 – 17.29	7.34 – 11.17	3.822
CO ₂	1.82 – 29.56	7.46 – 13.76	6.306
SF ₆	6.06 – 114.17	15.87 – 22.72	6.85

The least dense materials, He and H₂, exhibit the smallest range of output current. The denser material, CO₂ and SF₆, exhibit the larger ranges. The sensor current output does not clearly separate He and H₂. N₂, CO₂, and SF₆ are clearly distinguishable in Fig. 4. and Fig. 6. This may be attributed to the low density of the fluids or the sensitivity of the quartz crystal tuning forks.

TABLE II

Curve Fit Viscosity-Sensor Output Correlations

Fluid	Sensor Output – Viscosity Correlation	R-Squared
He	$y = 0.0288x^2 - 0.3564x + 20.799$	0.9306
H ₂	$y = 0.0392x^2 - 0.5298x + 10.632$	0.98
N ₂	$y = 0.0018x^2 + 0.0284x + 17.368$	0.9918
CO ₂	$y = 0.002x^2 - 0.0153x + 14.68$	0.9961
SF ₆	$y = 0.0005x^3 - 0.0272x^2 + 0.4602x + 12.719$	0.9526

The H₂, N₂, and CO₂ viscosity-sensor output correlations are all have very close quadratic and cubic fits as shown in the Table 2 Sensor Output-Viscosity Correlation column. The He and SF₆ viscosity-sensor output correlations have plateaus in this correlation at low pressures. The reason for these plateaus is a part of the ongoing work for this experiment.

IV. CONCLUSION

In this work we propose a commercially available tool to measure SCF viscosity to appropriately characterize dielectric material for ultra-fast MV and HVDC circuit breakers. This paper presents preliminary sensor measurements of CF₃I, He, H₂, CO₂, SF₆, and N₂ in the ambient lab environment with temperatures ranging from 19.3°C to 22°C. Measured sensor outputs were correlated with reference viscosities found in [15], [16]. By comparing sensor output and the reference viscosity

data of He, this study proves that the proposed method can accurately measure SCFs in a low-pressure environment.

ACKNOWLEDGMENT

This work has been supported, in part, by the National Science Foundation (NSF) grant #1944014, and by the Advanced Research Projects Agency–Energy (ARPA-E) grant DE-AR0001113.

REFERENCES

- [1] C. M. Franck, "HVDC circuit breakers: A review identifying future research needs," *IEEE Transactions on Power Delivery*, vol. 26, no. 2, 2011. doi: 10.1109/TPWRD.2010.2095889.
- [2] L. Graber, T. Damle, C. Xu, J. Wei, J. Sun, M. Mehraban, Z. Zhang, M. Saeedifard, S. Grijalva, J. Goldman, Q. Yang, K. Schoder, F. Peng, M. Steurer, and C. Park, "EDISON: A New Generation DC Circuit Breaker," in CIGRE Paris Exhibition, Aug. 2020.
- [3] C. Xu, J. Wei, and L. Graber, "Compatibility Analysis of Piezoelectric Actuators in Supercritical Carbon Dioxide," 2020. doi: 10.1109/EIC47619.2020.9158670.
- [4] L. Berger, "Dielectric strength of insulating materials," *CRC Handbook of Chemistry and Physics*. 2006.
- [5] N. Hill and M. Kurrat, "Discharge Mechanisms in Liquid Nitrogen-Breakdown Field Strength of Gaseous Nitrogen," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, 2018, doi: 10.1109/TASC.2018.2809460.
- [6] "VOLTESO 35," Mobil.ca. <https://www.mobil.ca/en-ca/lubricants/industrial/lubricants/products/products/voltesso-35>. (accessed Jul. 01, 2021).
- [7] J. Wei, A. Cruz, C. Xu, F. Haque, C. Park, and L. Graber, "A Review on Dielectric Properties of Supercritical Fluids," 2020. doi: 10.1109/EIC47619.2020.9158733.
- [8] J. Wei, A. Cruz, F. Haque, C. Park, and L. Graber, "Investigation of the dielectric strength of supercritical carbon dioxide-trifluoriodomethane fluid mixtures," *Physics of Fluids*, vol. 32, no. 10, 2020, doi: 10.1063/5.0024384.
- [9] J. Wei, A. Cruz, F. Haque, C. Park, and L. Graber, "Electrical Breakdown Characteristics of Supercritical Trifluoriodomethane-Carbon Dioxide (CF₃I-CO₂) Mixtures," in *2020 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Oct. 2020, pp. 427–430. doi: 10.1109/CEIDP49254.2020.9437475.
- [10] C. Park, J. Wei, P. Cheetham, C. H. Kim, S. Pamidi, and L. Graber, "The influence of temperature on the dielectric strength of gaseous cryogenics," in *Proceedings of the IEEE International Conference on Properties and Applications of Dielectric Materials*, 2018, vol. 2018-May. doi: 10.1109/ICPADM.2018.8401185.
- [11] D. Zeisel, H. Menzi, and L. Ullrich, "Precise and robust quartz sensor based on tuning fork technology for (SF₆)-gas density control," *Sensors and Actuators, A: Physical*, vol. 80, no. 3, 2000, doi: 10.1016/S0924-4247(99)00345-3.
- [12] Trafag AG, "8774 Gas Density Sensor with analogue and PWM output," <https://www.trafag.com/en/8774-gas-density-sensor-with-analogue-and-pwm-output/> (accessed May 10, 2021)
- [13] T. Choudhury and G. R. Biswal, "SF₆ density-and-viscosity sensing in Gas Insulated Switchgear using MEMS resonator," 2017. doi: 10.1109/ICPEICES.2016.7853174.
- [14] Y. Y. Duan, L. Shi, L. Z. Han, and M. S. Zhu, "Viscosity of saturated liquid trifluoriodomethane from 253 to 338 K," *Fluid Phase Equilibria*, vol. 162, no. 1–2, pp. 303–312, Aug. 1999, doi: 10.1016/S0378-3812(99)00216-2.
- [15] P. J. Linstrom and W. G. Mallard, "The NIST Chemistry WebBook: A chemical data resource on the Internet," *Journal of Chemical and Engineering Data*, vol. 46, no. 5, 2001, doi: 10.1021/jc000236i.
- [16] J. Hurly, K. A. Gillis, J. B. Mehl, and M. R. Moldover, "The viscosity of seven gases measured with a Greenspan viscometer," *International Journal of Thermophysics*, vol. 24, no. 6, 2003, doi: 10.1023/B:IJOT.0000004088.04964.4c