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Dielectric spectroscopic sensing of fine liquid droplets in an airstream

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ABSTRACT

Contamination of compressed air can reduce its utility and lead to costly failure of pneumatic components. Monitoring contaminants in the compressed air could help take preventive measures to maintain usefulness of the pneumatic systems. Dielectric spectroscopy has good potential as a viable commercial sensor technology for pneumatic systems as it can differentiate dielectric properties of the air with and without contaminants. It could also be used to detect the presence of oil mist, required for lubricating pneumatic components. Two tests were performed using a sensor capable of measuring the dielectric spectrum of the fluid mixture. The objective was to investigate the efficacy of dielectric spectroscopy in detecting the presence of deionised water and light lubricant oil in an airstream. These liquids were atomised using industrial spray nozzles, then entrained in an airstream and passed through the sensor. Spectroscopic measurements were acquired and multivariate classifiers were developed using principal component analysis and linear discriminant analysis to investigate the sensor's performance in differentiating the presence and absence of liquid droplets in the airstream. The classifier was able to separate the two cases suggesting dielectric spectroscopy could be used to detect these two liquids in an airstream.

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Introduction

Compressed air has multiple applications owing to its useful properties. It is used for power transmission and motion control in pneumatic systems, as well as inclusion into different processes like food packaging and processing. Because of its widespread use, it is also known as the fourth utility after water, electricity and natural gas (NREL, 2003). Among all these utilities, compressed air is the only one that can be generated onsite, and thus users have more control over its usage and quality.

However, the usefulness of compressed air can be negatively affected by ineffective compressed air systems. Less effective systems can decrease productivity of the air making it a very expensive entity. According to the survey from U.S. Department of Energy, about 10–30% of the electricity consumed in many facilities is used for compressed air generation. Furthermore, electricity costs constitute 76% of the cost of compressed air, while the remaining costs are due to maintenance and equipment (Shanghai and McKane 2008). Therefore, inefficient compressed air system can increase electric consumption and raise operational cost. Besides these, research shows that it is the most expensive form of energy available in the plant, since the conversion efficiency from electrical to pneumatic energy is as low as 10–19% (Shanghai and McKane 2008).

Technology that improves compressed air systems could have a significant impact. Improvement in compressed air systems can reduce electricity consumption by 20–50% or more, and thus save substantial expenses for energy (Saidur *et al*. 2010). Furthermore, a properly managed compressed air system can reduce maintenance and downtime costs, increase productivity and improve product quality.

Contamination of compressed air is one of the prime reasons for inefficient systems. Water is a typical contaminant found in compressed air, which can corrode and jam pneumatic systems, slowing down their operation. The presence of contaminants can also lead to system failure. Monitoring and filtering contaminants can reduce problems and improve the condition of compressed air. Early detection of these contaminants can help plant managers take preventive measures before catastrophic failures occur. Similarly, proper lubrication of pneumatic systems is important for reducing friction in pneumatic systems. As a result, lubricating oil reduces wear, increases longevity of the component and requires less maintenance.

Dielectric spectroscopy has potential as a sensing technology for detecting liquid droplets in compressed air. Dielectric spectroscopy is the measurement of dielectric properties of a material at multiple frequencies. The dielectric properties of a material explain the electrical

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interaction between the material and an electric field. Normally, this interaction depends on the frequency of the applied field and can be described best using relative complex permittivity, $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$. The real part ε_r' denotes the dielectric constant of the material and is a measure of the ability of the material to store electrical energy. The imaginary part, ε_r'', denotes the dielectric loss factor and is associated with the loss of energy in a material relative to the applied external electrical field. This relative complex permittivity of the material can be measured as a function of frequency using dielectric spectroscopy (Von Hippel 1954). Dielectric spectroscopy has been used for comparing different petroleum fractions(Tjomsland *et al.* 1996, Folgero 1998), sensing moisture dynamics in oil-impregnated pressboard (Sheiretov and Zahn 1995) and monitoring moisture content and insulation degradation in oil transformers (Koch and Feser 2004).

The goal of this project was to determine the performance of a sensor collecting dielectric spectroscopic measurements in detecting the presence of liquids, particularly water and lubricating oil, in an airstream.

Materials and methods

Tests were performed with deionised water and lubricant oil (Sunoco Sunvis 932, Sunoco, PA) using a cylindrical capacitive sensor. The sensor was originally developed and successfully used in a research project that investigated the capability of the sensor in detecting particulate contaminants in the hydraulic fluid (Kshetri *et al.* 2016). An experimental apparatus was built to produce fine droplets of these liquids and transport them through the dielectric sensor. Capacitance and dissipation factor of the airstream with and without these droplets were measured with an impedance analyzer (model 4192 LF, Hewlett-Packard, Palo Alto, CA, U.S.A.) connected to the sensor. The measurements were taken over the frequencies ranging from 1 to 13 MHz for deionised water and 100 kHz to 13 MHz for oil sampled linearly within decades. Finally, multivariate techniques such as principal component analysis (PCA) and linear discriminant analysis (LDA) were applied for analysis of the experimentally collected data.

Dielectric sensor design

The sensor used for the testing consisted of the housing, the sensing unit and the hydraulic adapter. The sensing unit is the major part of the sensor consisting of shields and electrodes assembled and fitted into the tubular passage formed by the two halves of the housing (Figure 1). The sensing unit was designed as a coaxial cylindrical capacitor in which the outer conductor and central rod form the two electrodes of the capacitive unit. The sensor works based on the principle that any medium between the two coaxial electrodes acts as a dielectric and has direct influence on the capacitance of the sensor. More detailed information on the design of the sensor can be found in Kshetri *et al.* (2016).

Experimental apparatus design

The experimental apparatus developed in the project consisted of industrial hydraulic nozzle to atomise liquids, a test chamber to facilitate effective channelling of aerosol through the sensor and a hydraulic circuit to meter liquids into the chamber. Industrial hydraulic atomising nozzles (model 1/4 LN, Spraying Systems Co., Wheaton, IL) were used to generate fine droplets of liquid contaminants to be entrained in the airstream. These nozzles were capable of producing droplets of sizes 10–500 microns in diameter.

An experimental chamber (Figure 2) was built for entrainment and transport of liquid droplets through the dielectric sensor. The chamber was primarily made up of .91-m-long PVC pipe with inside diameter of 0.10 m. The nozzle was connected in the middle of the pipe with the nozzle's orifice facing towards the pipe's outlet. The sensor was attached to the pipe using PVC reducers and

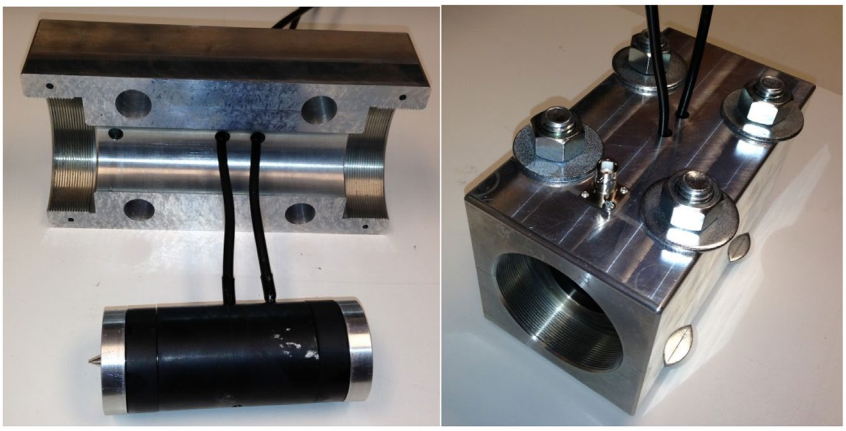


Figure 1. Sensor split housing design enables the assembly of the sensing unit and connection to cables (left) and complete assembly of the sensor (right).

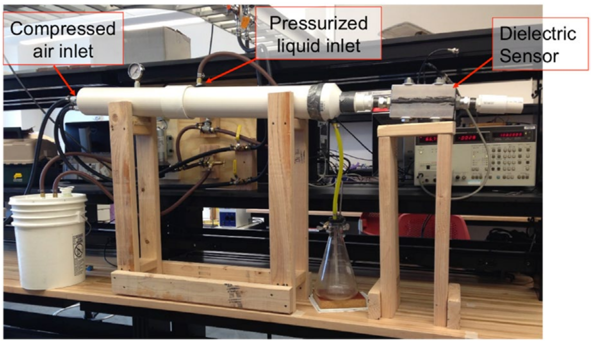


Figure 2. Experimental apparatus used for the test with deionised water shows the hydraulic circuit and impedance analyser used for the test.

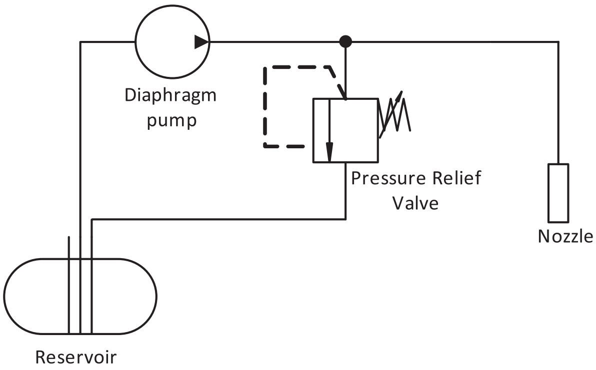


Figure 3. Schematic of hydraulic circuit used for metering liquids to the nozzle.

connectors. The sensor was mounted collinearly with the large chamber to allow effective movement of droplets out of the sensor. The appropriate sizes of PVC parts required for the chamber were identified based on model and simulation developed for liquid drop trajectory.

A small hose connected the experimental chamber with 2000-ml conical flask at the front-bottom section of the pipe. The 2000-ml flask was used to collect liquid from the bottom of the pipe resulting from the droplets coalescing in the inner surface of the pipe. Stands were built to support and adjust the orientation of the experimental chamber and sensor during the tests. The chamber was adjusted to a 10°–15° angle from horizontal so that the residue could easily flow to the conical flask without collecting inside the chamber.

A hydraulic circuit was developed to meter the test fluids into the experimental chamber. The hydraulic circuit consisted of a reservoir, diaphragm pump, pressure relief valve and hydraulic hoses (Figure 3). The diaphragm pump (model 8030-863-239, Shurflo, Cypress, CA) moved the test liquids from the reservoir to the nozzle. The pressure relief valve (model 110, Spraying Systems Co., Wheaton, IL) set the nozzle pressure to achieve the droplet characteristics and flow rate for the tests.

Test procedure

Two separate tests were conducted with: (1) deionised water and (2) air lubricating oil. These tests were conducted inside the lab where the temperature was relatively constant at 21 °C. Compressed air available in the lab was used to transport the atomised test liquids through the sensor. Compressed air was supplied at left end (Figure 2) of the long chamber. The effective flow rate of the air through the sensor was measured to be 40 cubic feet per minute (cfm) using an anemometer. An impedance analyzer (model HP 4192A LF, Hewlett-Packard, Palo Alto, CA, U.S.A.) acquired dielectric measurements of the fluid in the sensor during these tests.

The first test involved injecting deionised water into the airstream. A nozzle with a 0.5 capacity size was used for the tests. The 0.5 capacity size indicates that the nozzle can produce a flow rate of 0.5 gal/min (1893 ml/min) at 40 psi (276 kPa) inlet pressure. The test was replicated three times for spray and no-spray conditions. For each test, two cases were identified for data collection: spray and no-spray. ‘Spray’ represented a case in which fine liquid droplets, entrained in the airstream, passed through the sensor. ‘No-spray’ represented a case in which only air passed through the sensor (Table 1). Each sample represents measurement of capacitance and dissipation factor for a spectrum of frequencies acquired using the impedance analyser. For this test, the spectrum consisted of 13 different frequencies ranging from 1 to 13 MHz sampled linearly within decades. After each replication, the dielectric sensor was disassembled, cleaned and dried to avoid any possible variation in the data for different replications due to residue that may have collected inside the sensor after each test.

The second test was performed using the lubricating oil. A nozzle with a 1.5 capacity size was used for this test. A higher capacity size nozzle was required in comparison to test with deionised water because smaller capacity nozzles were unable to atomise the more viscous oil effectively. The test with oil also consisted of three replications, each consisting of 10–15 samples each for spray and no-spray conditions (Table 1). For this test, additional connectors were added at the outlet end of the dielectric sensor to channel oil droplets to a container inside a fume hood. This approach prevented unwanted exhaust of oil into the air. Additionally, the response of the sensor to oil droplets was mostly unknown since all the pilot tests were conducted solely with water as the test liquid. Therefore, for the test with oil, the frequency analyser measured capacitance and dissipation factor at 22 different frequencies ranging from 100 to 13 MHz, sampled linearly within decades.

Capacitance and dissipation factor were measured for these two cases at multiple frequencies. The data were then statistically analysed to find out effectiveness of the dielectric sensor in predicting presence of liquid droplets in the airstream.

Data analysis

Multivariate data analysis techniques were used to investigate the relationship of spectroscopic data containing capacitance and dissipation factor measurements to spray and no-spray classes. PCA was used to preprocess the data, and LDA was used for classification. The data was standardised before applying PCA by subtracting the mean from capacitance and loss factor values at each frequency and dividing the resultant by its standard deviation. This statistical standardisation ensures both capacitance and loss factor measurements are equally evaluated for their contribution in the analysis. For analysis, the data were initially split into training and test data-sets. The training data-set consisted of 2/3s of the original data that were randomly selected, and the remaining 1/3 of the samples were used as the test data-set. PCA was first applied on the training data-set, and the least number of principal components (PCs) explaining the most variation in the training data-set were identified. The data projected onto these principal components, also called scores, were then used to build the classifier based on LDA. The PCA loadings, obtained from the same lowest number of principal components of the training data-set, were used to rotate the test data-set and generate test scores. The classifier developed from training data-set was then applied on these test scores to investigate its efficacy in predicting test cases.

Results and discussion

Before developing classifiers, parallel coordinate plots (Figures 4 and 5) were developed for visual inspection of the data for spray and no-spray cases across different frequencies. The plots showed that the two cases separated distinctly for capacitance measurement (4(a) and 5(a)), while their separation was not clear for dissipation factor measurement (4(b) and 5(b)).

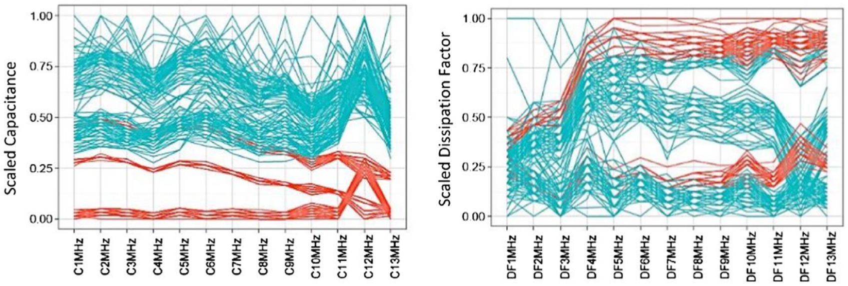
Table 1. Experimental design for the test with deionised water and light oil shows the replications performed, number of samples used and the cases used for training and test sets.

Tests with	Replications	Cases	Samples
Deionised Water	3	Spray	125
		No-spray	85
Light Oil	3	Spray	35
		No-spray	35

The capacitance of the sensor increased across all the frequencies when liquid droplets were entrained in the airstream as represented by higher scaled capacitance values for both the tests (Figures 4 and 5). This is probably because of the increase in the effective dielectric constant of the airstream due to presence of deionised water and oil, both of which have a higher dielectric constant than air. Air has a dielectric constant of 1, while deionised water and oil have dielectric constant of 80 and 3.9, respectively. Since capacitance is directly related to the dielectric constant, the increase in dielectric constant of the droplets and air mixture may have increased the capacitance measurements.

The classifiers developed for the two tests were also able to accurately separate the spray and no-spray cases. For both the tests with deionised water and oil, the first two principal components (PCs) were enough to explain 93 and 92% of the variation in the data, respectively. Therefore, first two principal components were chosen for rotation of the measured dielectric data. Figures 6 and 7 show the resulting PCA scores plotted on the selected principal components for deionised water and oil, respectively. The PCA scores of the test data-set were also projected on the same principal components and can be observed on Figures 6 and 7 for the respective tests.

Both PCA plots (Figures 6 and 7) show that the variations in the measurements were not only due to spray and no-spray cases, but also due to differences in the replications. However, prior knowledge of the observations allow grouping of the two cases as illustrated by the dotted 95% confidence ellipse surrounding the data points. The 95% confidence ellipse for each case was developed using both training and test data points for that case. The ellipses delineate the area where the mean of the two cases will lie with a 95% confidence. Since data points for spray and no-spray cases are distinctly separated in the plane formed by two principal components, a classifier developed using LDA was able to predict both training and test data accurately (Tables 2 and 3).



(a) (b)

Figure 4. (a) Capacitance and (b) dissipation factor values scaled to minimum zero and maximum one for spray (blue lines) and no-spray (red lines) cases across multiple frequencies for tests with deionised water.

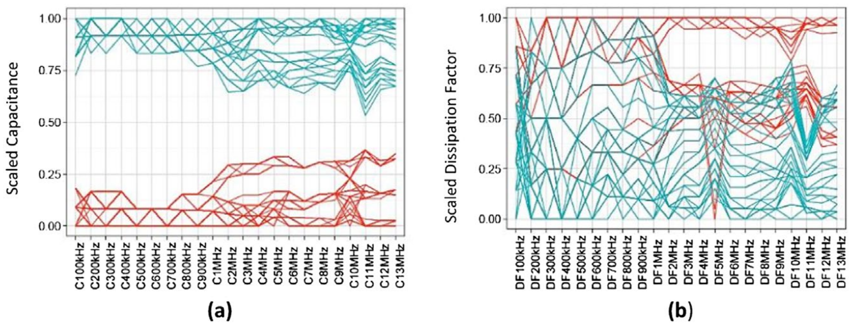


Figure 5. (a) Capacitance and (b) dissipation factor values scaled to minimum zero and maximum one for spray (blue lines) and no-spray (red lines) cases across multiple frequencies for tests with light oil.

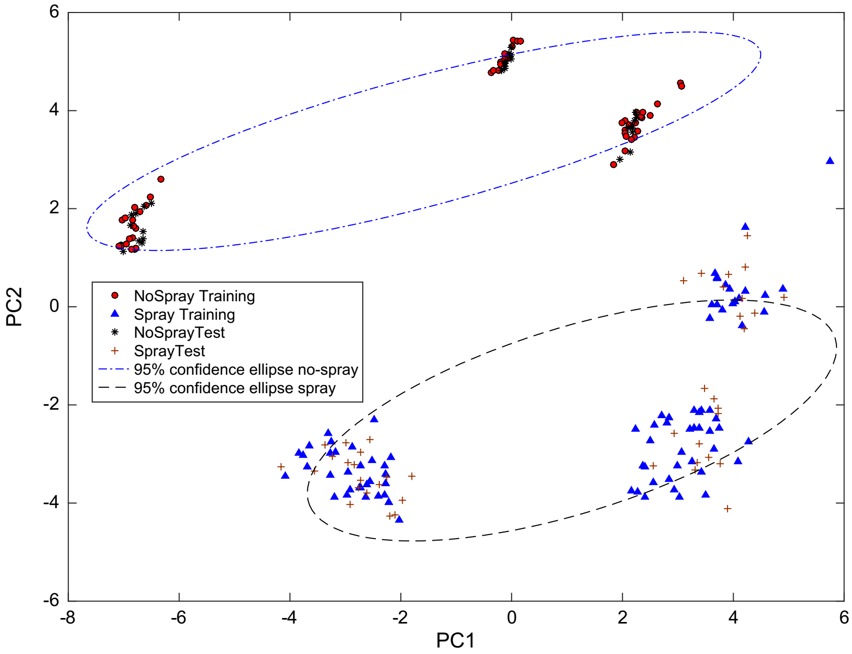


Figure 6. Dielectric spectroscopic data from the test with water projected on the first two principal components.

Note: Circles and triangles represent data points for training data-set, while asterisks and plus signs represent data points for the test data-set. Dotted ellipses represent 95% confidence ellipse for the respective spray and no-spray cases.

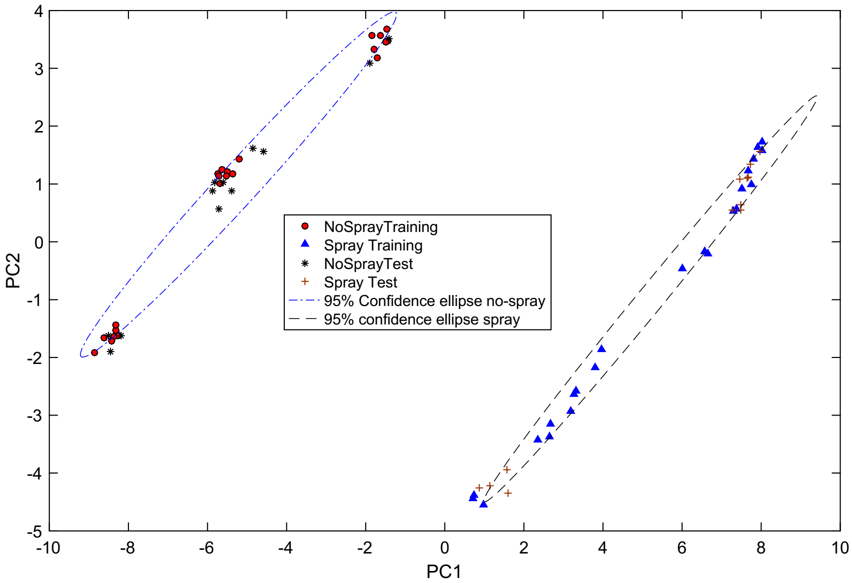


Figure 7. Dielectric spectroscopic data from the test with oil projected onto the first two principal components.

Notes: Circles and triangles represent data points for training data-set, while asterisks and plus signs represent data points for the test data-set. Dotted ellipses represent 95% confidence ellipse for the respective spray and no-spray cases.

Table 2. Misclassification table for training (left) and test (right) data-sets for test with deionised water.

Training set			Test set		
	No-Spray	Spray		No-Spray	Spray
No-Spray	57	0	No-Spray	28	0
Spray	0	83	Spray	0	42

Table 3. Misclassification table for training (left) and test (right) data-sets for test with light oil.

Training set			Test set		
	No-Spray	Spray		No-Spray	Spray
No-Spray	23	0	No-Spray	12	0
Spray	0	23	Spray	0	12

The result from the test with deionised water (Table 2) showed that the classifier developed using the training data-set was able to predict all 57 no-spray and 83 spray cases in the training data-set accurately. This classifier also predicted all 28 no-spray and 42 spray cases in the test data-set.

Similar results were observed with light oil (Table 3). The classifier developed for the analysis was accurately predicted both cases in the training and test data-set. For the training set, the classifier predicted all no-spray and spray cases without any errors. It also accurately predicted all 12 no-spray and spray cases in the test data-set.

These results showed that the dielectric sensor was successful in capturing the differences in dielectric properties of the airstream due to the presence and absence of liquid droplets in both the tests.

Conclusions

Following conclusions can be drawn from the rsearch:

(1) Dielectric spectroscopic sensing has good potential to be used for detecting the presence of water and oil droplets in an airstream.
(2) The presence of water and oil droplets changes the effective capacitance of the airstream, and this knowledge could be used to detect these liquids using capacitive sensing techniques.

Disclosure statement

No potential conflict of interest was reported by the authors.

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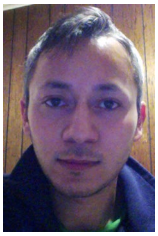
Notes on contributors



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References

Folgero, K., 1998. Broad-band dielectric spectroscopy of low permittivity fluids using one measurements cell. *IEEE Transactions on Instrumentation and Measurement*, 47 (4), 881–885.

Koch, M. and Feser, K. 2004. Reliability and influences on dielectric diagnostic methods to evaluate the ageing state of oil-paper insulations. Available from: www.unistuttgart.de/ieh/forschung/veroeffentlichungen/2004_aptadm_koch.pdf [accessed 18 May 2014]

Kshetri, S., Steward, B.L., and Birrell, S.J., 2016. Dielectric spectroscopic sensor for particle contaminant detection in hydraulic fluids. *International Journal of Fluid Power*, 1–9. doi:10.1080/14399776.2016.1210422.

National Renewable Energy Lab., Golden, CO. (US). 2003. Improving compressed air system performance: a sourcebook for industry (No. DOE/GO-102003-1822). Available from http://www.osti.gov/scitech/biblio/15006054.

Saidur, R., Rahim, N.A., and Hasanuzzaman, M., 2010. A review on compressed-air energy use and energy savings. *Renewable and Sustainable Energy Reviews*, 14 (4), 1135–1153.

Shanghai, H.Q. and McKane, A., 2008. Improving energy efficiency of compressed air system based on system audit. Lawrence Berkeley National Laboratory. Available from http://escholarship.org/uc/item/13w7f2fc.

Sheiretov, Y. and Zahn, M., 1995. Dielectrometry measurements of moisture dynamics in oil-impregnated pressboard. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2, 329–351.

Tjomsland, T., Hilland, J., Christy, A.A., Sjoblom, J., Riis, M., Friis, T., and Folgero, K., 1996. Comparison of infrared and impedance spectra of petroleum fractions. *Fuel*, 75 (3), 322–332.

Von Hippel, A.R., 1954. *Dielectric materials and applications*. New York, NY: The Technology Press of M.I.T and John Wiley and Sons.