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Dielectric Spectroscopic Aerosol Sensing in the Compressed Air Stream

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ABSTRACT. *Contamination of compressed air can reduce its utility and lead to costly failure of pneumatic components. Monitoring the presence of contaminants in the air could provide early warning to take measures that could retain pneumatic system usefulness. The sensing of contaminants in a compressed air stream using dielectric spectroscopy has good potential for a viable commercial sensor for pneumatic systems based on the differences in dielectric properties between air and common contaminants such as metal, silicon, and water condensate. Oil mist, while not a contaminant, is required for lubricating pneumatic components, so its presence is important. Two tests were performed using a dielectric sensor capable of spectroscopic measurement to investigate the efficacy of dielectric spectroscopy in detecting the presence of liquids (water and oil) in compressed air. The first test used deionized water, and the second test used a light lubricant oil (Sunoco Sunvis 932, Sunoco, PA). Industrial spray nozzles were used to atomize these liquids, which were then entrained in a compressed airstream and passed through the dielectric sensor. Visualization of spectroscopic measurements and their transformation using principal component analysis (PCA) showed that the sensor has potential to differentiate the presence and absence of liquid droplets in compressed airstream. This separation of two cases based on the spectroscopic data suggests that dielectric spectroscopy could be used to detect these two liquids in the compressed airstream.*

Keywords. *Dielectric spectroscopy, PCA, compressed airstream, aerosol.*

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). Unlike these other utilities, it can be generated onsite, and thus users have more control over its usage and quality.

However, inefficiency in compressed air systems can greatly reduce its utility. Low efficiency will not only lead to decrease in its productivity, but also make it a very expensive entity. According to the survey from U.S. Department of Energy, about 10% to 30% of the electricity consumed in many facilities is used for compressed air generation. Electricity costs constitute 76% of the cost of compressed air while the remaining costs are due to maintenance and equipment. 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 to 19 % (Shanghai and McKane, 2008).

Technology that improves compressed air systems could have a significant impact. A study has shown that improvement in compressed air systems can reduce electricity consumption by 20% to 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.

Dielectric spectroscopy has potential as a technology for detecting contaminants 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 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, 1954a). Dielectric spectroscopy has been used for comparing different petroleum fractions (Folgero, 1998; Tjomsland, et al., 1996), sensing moisture dynamics in oil impregnated pressboard (Sheiretov & Zahn, 1995), and monitoring of moisture content and insulation degradation in oil transformers (Koch & 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 air stream.

Materials and Methods

Tests were performed with deionized water and lubricant oil (Sunoco Sunvis 932, Sunoco, PA). An experimental apparatus was built to produce droplets of these liquids and transport them through the dielectric sensor. The capacitance and dissipation factor of the compressed airstream with and without these droplets were measured with an impedance analyzer (model 4192 LF, Hewlett-Packard, Palo Alto, CA, USA) using a dielectric sensor. The measurements were taken over the frequencies ranging from 1MHz to 13 MHz for deionized water and 100 kHz to 13 MHz for oil sampled linearly within decades. Finally, principal component analysis (PCA) was used for analysis of the experimentally collected data.

Experimental Apparatus Design

The experimental apparatus developed in the project consisted of three main parts. They were: 1) a mechanism to atomize liquids, 2) a test chamber to facilitate effective channeling of aerosol through the sensor, and 3) a hydraulic circuit to meter liquids into the chamber.

1) Atomizing Mechanism

Industrial hydraulic atomizing nozzles (model 1/4 LN, Spraying Systems Co., Wheaton, IL) were used to generate fine droplets of liquid contaminants that could be entrained in the airstream. These nozzles were capable of producing droplets of sizes 10 to 500 microns in diameter.

2) Experimental Chamber

An experimental chamber (figure 1) was built for entrainment and transport of liquid droplets through the dielectric sensor. The chamber consisted of a long PVC pipe with relatively larger diameter enclosing the spray area, and smaller PVC pipes and fittings for proper attachment with the dielectric sensor. A model of liquid droplets trajectory was developed and the simulation was used to identify the appropriate sizes of PVC parts required for the chamber. The sensor was connected collinearly with the large chamber to allow effective movement of droplets out of the sensor.

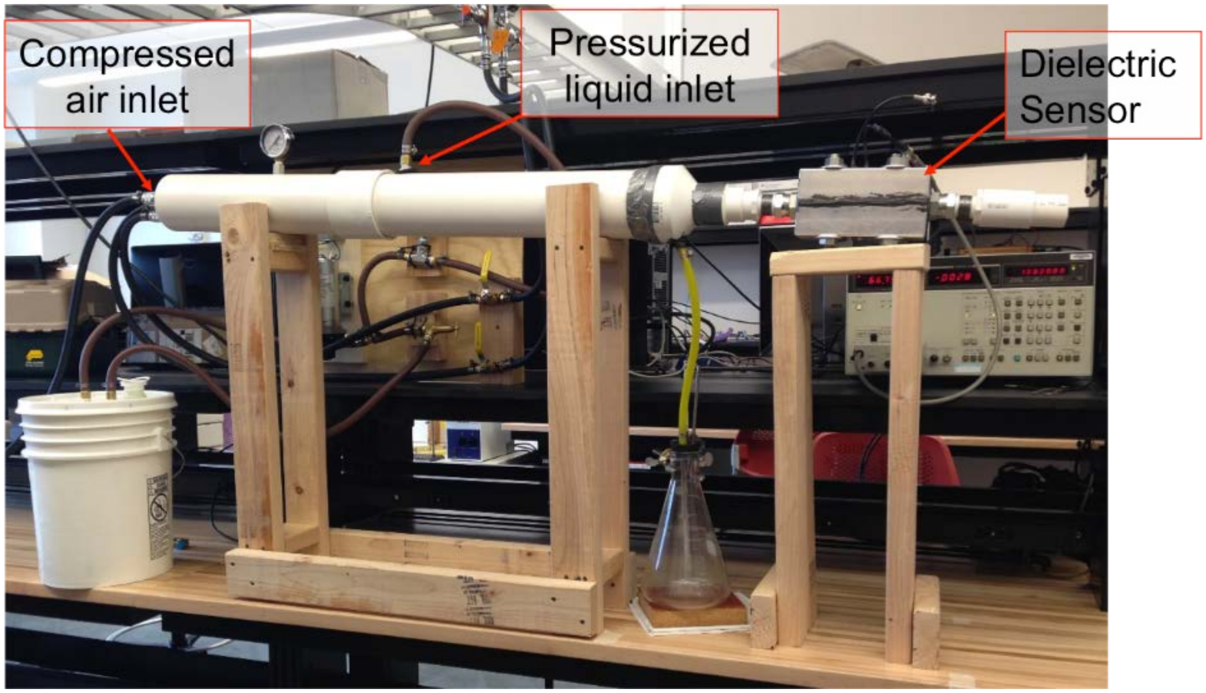


Figure 1. Experimental apparatus used for the test with deionized water shows the hydraulic circuit and impedance analyzer used for the test.

The section of the chamber enclosing the spray area was selected to be a four inch in diameter and consisted of two PVC pipes of different length attached by a coupler. Two pipes were used rather than a single long pipe to ease disassembly and adjustments between the tests.

The chamber had attachments for the liquid nozzle and a hose connection to a 2000 ml conical flask at the top-middle and front-bottom sections of the pipe, respectively. The 2000 ml flask was used to collect liquid from the bottom of the pipe when droplets came in contact the inner sides of the tube and coalesced. Wooden 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 degree from horizontal angle so that the residue could easily flow to the conical flask without collecting inside the chamber.

3) Hydraulic Circuit

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 2). 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 required droplet characteristics and flow rate for the tests.

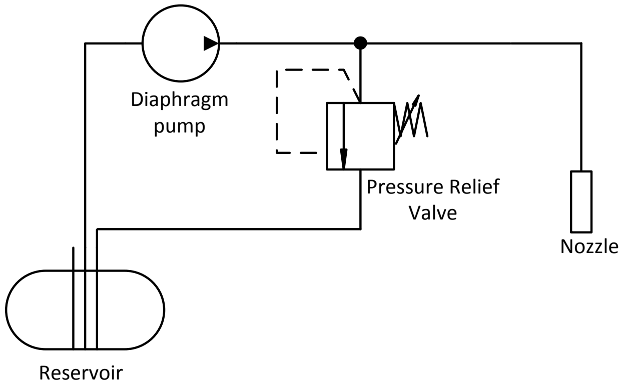


Figure 2. Schematic of hydraulic circuit used for metering liquids to the nozzle

Dielectric Sensor

A dielectric sensor (figure 3) was used for the test. The dielectric sensor is a capacitive sensor primarily consisting of housing and sensing unit. The housing encloses and supports the sensing unit, and has ports for hydraulic connections. The sensing unit consists of a number of cylindrical components functioning as electrodes and shields for taking dielectric measurements. More information on the dielectric sensor can be found in Kshetri (2015).

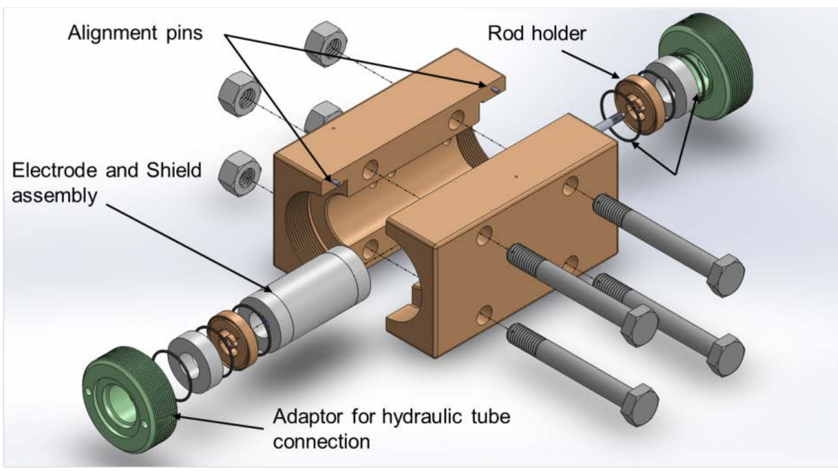


Figure 3. Exploded view showing flow-through design of the sensor and arrangement of different metallic parts and dielectric assembled

Test Procedure

Two separate tests were conducted with: 1) deionized water and 2) air lubricating oil (Sunvis 932, Sunoco, Philadelphia, PA). These tests were conducted inside the lab where the temperature was relatively constant at 21 degrees Celsius. Compressed air available in the lab was used to transport the atomized test liquids through the sensor. The air was supplied at the rear end of the long chamber using three sources of compressed air. The effective flow rate of the air through the sensor was observed to be 40 cubic feet per minute (cfm). An impedance analyzer (model HP 4192A LF, Hewlett-Packard, Palo Alto, CA, USA) was used for taking dielectric measurements of the fluid in the sensor during these tests.

The first test for contaminants in pneumatic systems involved injecting deionized water into the air stream. 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, and each replication consisted of more than 25 samples, each for spray and no-spray conditions. The impedance analyzer measured capacitance and dissipation factor at 13 different frequencies ranging from 1 MHz to 13 MHz sampled linearly within decades. After each replication, the dielectric sensor was disassembled, cleaned and dried. This disassembly was done to avoid any possible variation in the data for different replications because of residue that may have collected inside the sensor after each test.

The second test was performed using lubricating light oil. A nozzle with a 1.5 capacity size was used for this test. A higher capacity size nozzle than that used for the water experiment was required because smaller capacity nozzles were unable to atomize the more viscous oil effectively. The test with oil also consisted of three replications, each consisting of 10 to 15 samples for spray and no-spray conditions. Unlike the test with deionized water, the experimental apparatus was not disassembled during the test with oil, and all three replications were performed sequentially at once with alternating spray and no-spray conditions. For this test, additional connectors were added at the outlet end of the dielectric sensor to channel oil droplets to collect in 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 analyzer measured capacitance and dissipation factor at 22 different frequencies ranging from 100 kHz to 13 MHz, sampled linearly within decades.

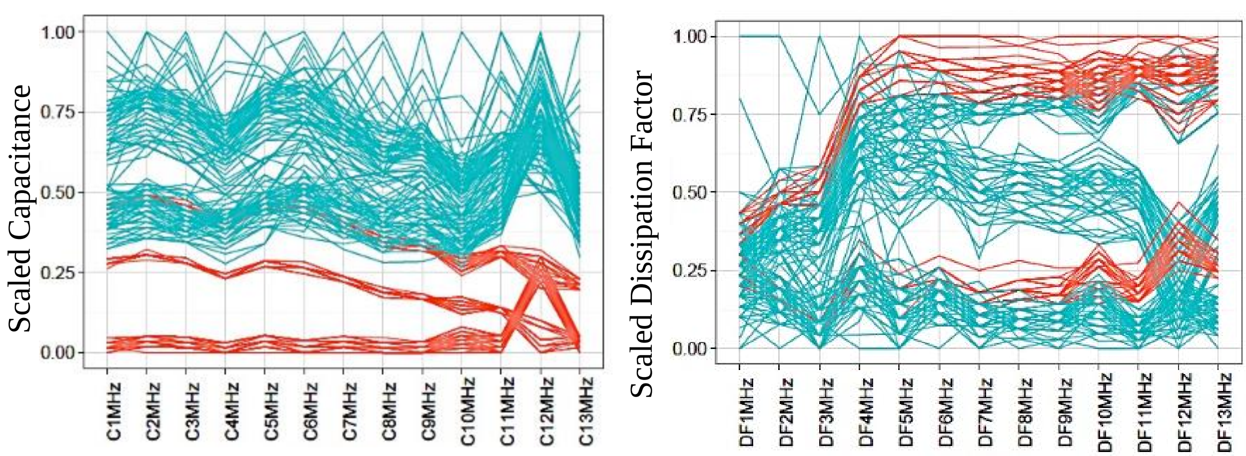
For each test, two cases were identified for data collection: spray and no spray. “Spray” represented a case in which fine liquid droplets, entrained in the compressed air, passed through the sensor. “No-spray” represented a case in which only compressed air passed through the sensor. Capacitance and dissipation factor were measured for these two cases at multiple frequencies. These dielectric data were then statistically analyzed to find out the effectiveness of the dielectric sensor in predicting the presence of the liquid droplets in the compressed air.

Table 1. Experimental design for the test with deionized 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
Deionized Water	3	Spray	125
		No-spray	85
Light Oil	3	Spray	35
		No-spray	35

Results and Discussion

The visual inspection of the data for both the tests showed that there was distinct variations in the capacitance measurements (4a and 5a) for spray and no spray cases. While the variation in dissipation factor measurements was not very clear (4b and 5b). The capacitance of the sensor increased across all the frequencies when liquid droplets were entrained in the airstream. This effect was probably because of the increase in the effective dielectric constant of the compressed air stream due to presence of deionized water and oil, both of which have a higher dielectric constant than air. Air has dielectric constant of 1, while deionized water and oil have dielectric constant of 80 and 3.9 respectively. Since capacitance has direct relationship with dielectric constant, the increase in dielectric constant of the compressed may have increased the capacitance measurements.



(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 deionized water.

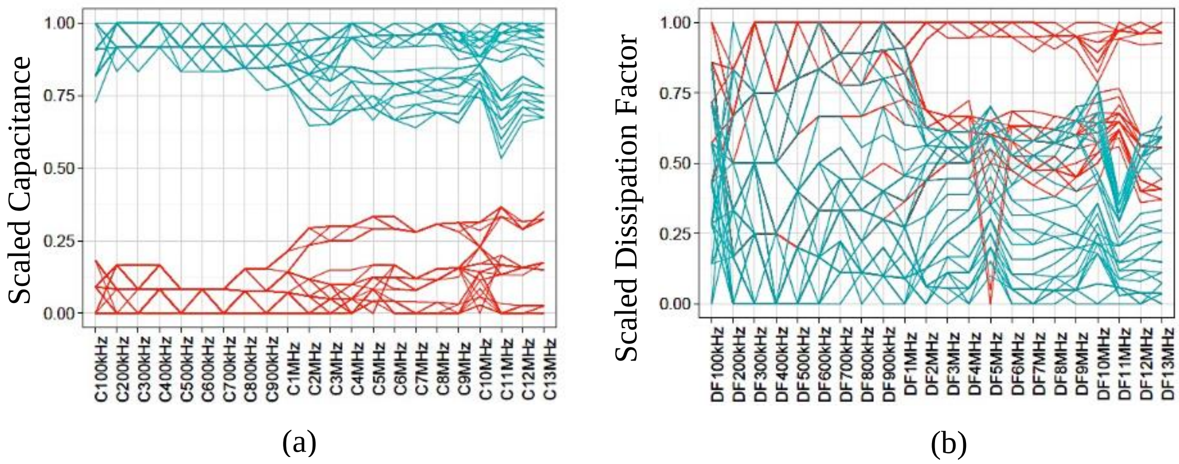


Figure 5. (a) Capacitance and (b) dissipation factor values scaled to minimum zero and maximum one for spray (blue lines) and no-spray (red lines) cases across multiple frequencies for tests with light oil.

The spray and no-spray cases for the tests with deionized water and oil were completely separable when data were transformed using principal component analysis (PCA). PCA transformed the data by projecting them onto linearly uncorrelated principal components (PC). The projected data on principal components are called scores. For tests with deionized water and oil, the first two principal components were enough to explain 93% and 92% of the variation in the data, respectively. Therefore, first two principal components were chosen for transformation of the measured dielectric data. Figure 6 and 7 show the resulting PCA scores plotted on the selected principal components for deionized water and oil respectively.

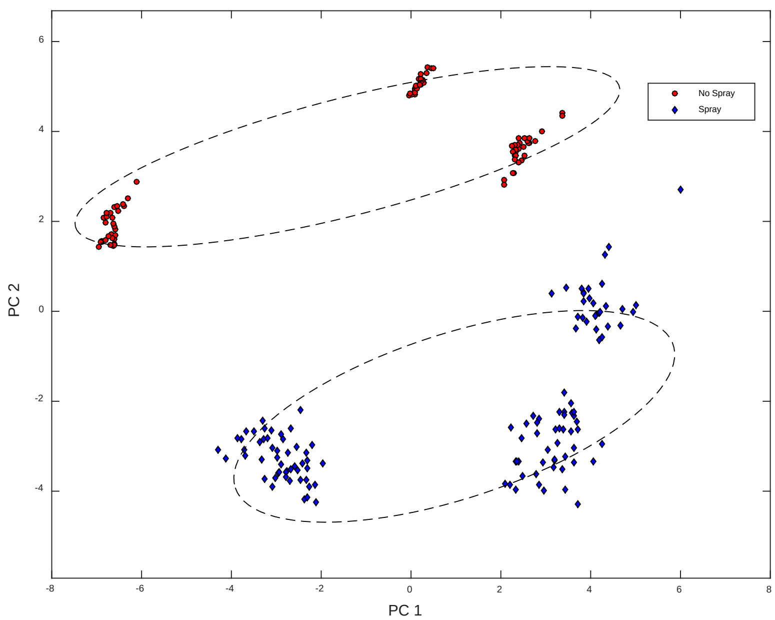


Figure 6. Dielectric spectroscopic data from the test with deionized water projected on the first two principal components. Red and Blue represent data points for no-spray and spray cases respectively.

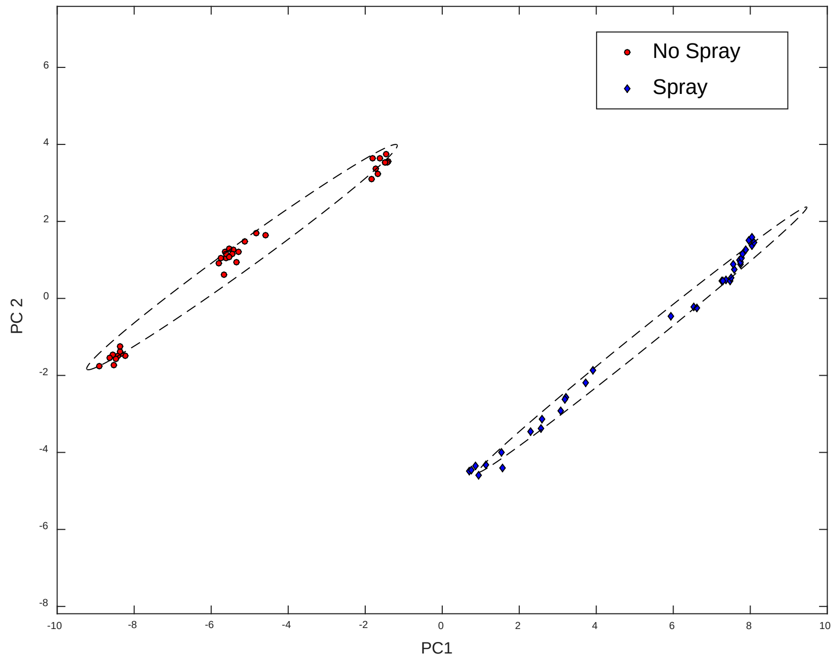


Figure 7. Dielectric spectroscopic data from the test with oil projected onto the first two principal components. Red and Blue represent data points for no-spray and spray cases respectively.

Both these plots 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. Since data points for spray and no-spray cases are distinctly separated in the plane formed by two principal components, it shows that dielectric sensor was successful in capturing the differences in dielectric properties of the air stream due to the presence and absence of liquid droplets in both the tests.

Conclusions

From this research, it can be concluded that the dielectric spectroscopic sensing has potential to be used for the detection of the presence of oil and water droplets in the compressed airstream.

Acknowledgements

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