AUTOMATED CONTROL OF ELECTRONIC CIGARETTE EVALUATION SYSTEM

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ABSTRACT

The primary objective of the Electronic Cigarette Evaluation System Phase II project was to improve the design of the Electronic Cigarette Evaluation System (ECES). The system is intended to simulate the operation of commercially available electronic cigarettes and collect the resultant vapors in order to facilitate further research on the contents of those vapors. In order to achieve these aims, a closed loop control system with flow-rate feedback was developed and implemented. Driven by a controlled vacuum reservoir, a collection bag “smokes” the electronic cigarette, collecting all vapor products produced. Compared to benchmark data obtained from the ECES at the beginning of development, the Phase II system provides an accuracy of ±2% on total intended puff volume, improving on the benchmark of ±5%. In addition, the control output can be controlled at a rate of 20 Hz, enabling full resolution of input flow profiles out to a corner frequency of 1.5Hz. These improved characteristics in comparison to the Phase I ECES, combined with automated control of the system greatly improve the capabilities of the system.

NOMENCLATURE

DAQ – Data acquisition device
Electronic Cigarette – A device relying on electric power to produce a nicotine rich vapor that is driven by the user’s puff
ECES – Electronic Cigarette Evaluation System
FDA – Food and Drug Administration
GUI – Graphical user interface
LabView – A software suite produced by National Instruments designed to operate digital and analogue electronic devices.
PI/PID- Refers to Proportional, Integral and Proportional, Integral, Derivative Controller Types
STP – Standard temperature and pressure: 273 K (0°Celsius) and 1 atmosphere pressure
Vapor - Diffused matter (as smoke or fog) suspended in air and impairing its transparency. [1]

INTRODUCTION AND BACKGROUND

This project is considered a “second generation” of electronic cigarette data collection and analysis at the Rochester Institute of Technology. The FDA has done introductory level experiments with the product to ultimately determine a potential basis for regulations within the USA; they have not obtained indicating results with their analysis suitable for definitive legislation. Currently, based upon U.S. Court of Appeals for the District of Columbia Circuit in Sotterra, Inc. v. Food & Drug Administration, electronic cigarettes are classified as a tobacco product, and regulated as such, unless directly marketed for therapeutic purposes [1]. The case specifically argued whether Congress had authorized the Food and Drug Administration to regulate electronic cigarettes under the drug and device provisions of
the Federal Food, Drug, and Cosmetic Act, or under the Family Smoking Prevention and Tobacco Control Act of 2009 [1]. This proved an important decision as it allowed electronic cigarettes to be regulated as a combustible cigarette, instead of a dosing device. This is an important decision as many different drug cartridges exist in addition to nicotine cartridges that are used within the electronic cigarette system to simulate combustible cigarette smoking.

A previous project, P10055, has designed an apparatus to collect vapor and particulate matter, as well as operate in a manor representative of an actual 50th percentile smoker’s standard draw technique. Project 12055’s design has used much of the existing system architecture with numerous improvements to the system operation and controls. The absence of reliable data regarding electronic cigarette vapor emissions and composition is the main driving force behind our project.

The objective of the project was to improve the design of the Electronic Cigarette Evaluation System that smokes an electric cigarette driven by a set time interval & draw rate. The desired result is a system that can test the hypothesis that electronic cigarettes contain fewer carcinogens, little or no particulate matter, and are less harmful than their combustible driven cigarettes counterparts, while delivering an equivalent amount of nicotine to a combustible cigarette. To achieve this, the previous system was revamped, with a focus on the further development of the controls system in a manner that will accurately accommodate and simulate the natural way a smoker would draw on a combustible cigarette.

**PROCESS AND METHODOLOGY**

The methodology behind the operation of the system is based upon the basic principles of fluid mechanics and transport phenomena. The system was constructed in a manner as such that it replicates the human lung. The basic operation is simple in method. The primary control variable for a smoking test is total vapor volume inhaled into a collection apparatus (gas chromatography sample collection bag). Due to simpler sensing implementation, inhaled volume is observed by monitoring flow rate through the electronic cigarette system. To effectively control the flow rate across the electronic cigarette device and into a collection apparatus, a constant vacuum must be applied to the bag, and the total flow resistance across the inlet system (electronic cigarette included) is controlled. These aims are achieved by using two proportional control valves and two individual closed control loops. A vacuum pump draws constant vacuum on one proportional valve, controlling vacuum to a vacuum tight box containing the collection bag. A pressure transducer is used for feedback to this first control loop. On the other side of the system, a flow meter, proportional valve and e-cigarette are arranged in series in such a manner that the electronic cigarette sits after the flow meter as to prevent contamination of the device. The proportional valve here controls the rate of flow into the collection bag, using the flow meter in series as feedback. Effectively, flow into and out of an airtight box is independently controlled in order to carefully manage flow across a test cigarette. A flow chart diagram of the system can be seen below in Figure 1: System Control Process.

The mechanics behind the system’s operation provide many benefits that allow for expanded system features. The primary advantage of the newly implemented closed loop flow control is the ability to test using generic or user generated smoking profiles. The means to accurately match any input flow profile allows the researcher to devise integrated test experiments which combine test data from actual subjects and simulated smoking events. The complete and accurate integration of behavioral data matched with controlled vapor collection provides the researcher with a more complete picture than any current smoking test machines provide.

![Figure 1: System Control Process](image-url)
CONTROL SYSTEM DESIGN

The primary method used to implement closed control in both the vacuum and flow control loops is the standard PID controller. The PID controller was chosen because it provides effective, stable, tunable performance. Terms can be added or removed, reducing the order of the controller, as necessary. In addition, robust experimental techniques are widely known to tune these controllers in place, without a priori knowledge of the exact system model. Ziegler-Nichols is an example of one of these methods, and was the intended choice. The precise performance of the system was not known well enough in design to build successful first pass controllers, so this feature was of critical performance. Seen below in Figure 2: Generic PI Control is the generic PID control loop, representative of what was implemented for this device.

![Figure 2: Generic PI Control](image)

It was originally assumed that derivative control would not be necessary for effective control of our system. Both of the controlled systems, vacuum and flow rate were anticipated to have first order responses, which requires only proportional and integral control terms in the compensator. While benchmarking the existing system, this was confirmed, but in retrospect, our benchmarking techniques were not representative of an actual control system. The benchmarking procedure entailed fully opening the system’s proportional valve, which failed to properly demonstrate the proportional valve’s inherent time delay, hysteresis and dead zone characteristics. The valve’s manufacturer specified valve performance, but it is now believed that the manufacturer’s compiled data was somewhat optimistic.

For the vacuum control loop, these factors did not create major issues. The vacuum system is highly damped and demonstrates highly first order behavior. Ziegler-Nichols techniques were used effectively to find approximate integral and proportional constants, and these were further tuned by hand for optimal results. For the flow control system however, these factors resulted in a significantly more unstable system than originally anticipated. Compared to the vacuum system, the total flow resistance was similar, but the required flow rates much smaller. In addition, the proportional valve used had a larger time delay and hysteresis than suggested in published data. Ziegler-Nichols open loop tuning methods were again used to find approximate PI constants, but significant oscillation continued to exist. True stability could only be reached with extensive hand tuning. In order to reach acceptable settling times, the controller gains had to be pushed so far that the system was always on the edge of marginal instability.

In order to improve the function of the controller, it was decided to add derivative control to the flow rate controller. Including derivate control allows reduction in the settling time of a step response, and allows the proportional gain of the controller to be increased, reducing rise time. In order to reduce high frequency, stochastic noise from the flow meter, a low pass filter was used upstream from the controller with a 20Hz corner frequency. Alternately, a tuned lead-lag compensator could be implemented in place of the derivative/low-pass combination, but tuning may be more challenging.

Ultimately, the vacuum control compensator loop was tuned to a stable, effective point. Its performance was never critical to the function of the system, but its response times and stability nonetheless were easily tuned to remain stable over a wide range of operating points. The flow control loop was also tuned acceptability, although it
represents a potentially unstable control case if operated far from its typical state. The stability of the system is highly dependent on the total flow resistance of the inlet path, and it may not remain stable with a lower resistance in place. Removal of the cigarette, or attempting to test a cigarette with exceptionally low flow resistance could result in an unstable response. If encountered, this can be remedied by including some additional resistance in the flow path, in the form of an orifice plug in the flow meter or some other method of achieving slightly higher total flow resistance.

**PHYSICAL SYSTEM DESIGN**

In improving the system, the footprint of the system was greatly consolidated, with an emphasis on containing the system in a simple fixture that contains all necessary components needed for operation. The overall goal of this consolidation was to improve throughput of testing while providing a more robust and durable test fixture which would withstand the needs of future research. In constructing the new system with a reduced footprint, there were many specific driving needs that drove the improvements that were made in order to achieve a more robust system.

A main component of the system, the vacuum chamber, was deemed to be a weakness of the system due to the materials and shape used in previous design. The previous vacuum chamber also experienced problems sustaining the vacuum pressure needed to operate the system. In order to improve this design, a new vacuum chamber was created through the modification of a Pelican hard case. Through prototype testing, it was determined that a Pelican Model 1450 would be used as the case withstood the vacuum levels needed to sustain the system, while providing a volume big enough to accommodate multiple sample collection bag sizes. This also allowed for the custom placement of all needed fittings in order to provide a shortened flow path and allow for consolidation of main system questions.

In order to provide power to the system, a redesigned electrical grid was designed in order to accommodate the expanded electrical needs to the system. This resulted in a consolidated electrical system board that contains power supplies, the vacuum transducer, proportional valve power boards, solid state relays and DAQ in a single location. It was also made removable, as so the user can remove the board and relocate all main electrical and flow connections from the main fixture to an outside placement for easy access for troubleshooting, or for further development and integration of future components. Implementing the wiring system into the overall system design by mounting the box to an aluminum frame reduced the distance wires needed to be run.

Various components of the system were also custom fabricated in order to achieve the needs of the improved system. A major component of the system that was fabricated is the fixture itself. The fixture consists of 1/8” thick Aluminum plates welded together to provide a ridged structure to mount the box, pump, and electrical board in a secure and safe matter away from the testing interface. The fixture also allowed for the placement of all the system components in close proximity, allowing for the required reduction of tubing and wiring for the system.

Another major component that was created was the electronic cigarette manifold. The purpose of this manifold is to allow the electronic cigarette to be placed directly in the flow path, but between the flow meter and the inlet proportional valve. The e-cigarette manifold simply allows air from the flow meter to enter the chamber while also allowing the electronic cigarette to be mounted downstream within the same chamber, essentially placing the cigarette between the flow meter and proportional valve components. Therefore, this design change is crucial to the accuracy of the flow meter as it prevents the contamination that occurs from the emissions of the electronic cigarette. This change has multiple benefits because the contamination not only decreases accuracy of the feedback to the system; it also requires the flow meter to be professionally cleaned and calibrated. Not only is the accuracy of the flow rate data improved, but reducing the effective flow path between the electronic cigarette and the collection bag also improves accuracy of the collected data. Other items such as handles and hinges were also mounted to the fixture for ease of transportation and operation. The fixture was also powder coated due to its inert properties.

Reducing the flow path was essential, which was achieved by reducing the overall amount of tubing used the Phase II design over the previous Phase I design. This was a direct result of meeting the requirements for a reduced flow path for the flow of vapor into the sample collection bag. In order to ensure collection of all vapors that is collection, the tubing needed to be inert, as well as resistant to methanol, which is used to collect the sample for gas chromatography analysis. For this reason, Fluorinated ethylene propylene (FEP) was used for the flow path.

At the end of the flow path, it was also necessary to provide a robust solution for the collection of the emitted nicotine rich vapor. The was achieved by utilizing gas chromatography sampling bags that are also resistant to the methanol used to collect the nicotine for gas chromatography testing. The bags recommended to be utilized by the system are made of FEP, or are of a Multiple Foil layer construction consisting of 5 separate layers. These five layers consist of an outer layer of 60 gauge Nylon, Metalized Aluminum (two separate layers), and
Polyethylene (two separate layers). This allows for the sample to be collected in an inert atmosphere which is resistant to sunlight, outside contamination, as well as leaking. Leaking from the bag is prevented by a standard dual purpose Propylene valve which also contains an internal septum as well as an on-off valve.

The final system can be seen below in Figure 3: ECES Front, and Figure 4: ECES Back. A representative sample of the gas sampling bag can be seen in Figure 5: Sample Collection Bag.

**Figure 3: ECES Front**

**Figure 4: ECES Back**

**Figure 5: Sample Collection Bag**

**USER INTERFACE**

A complete GUI for system operation and user interface was developed within the Labview environment. Significant ergonomic improvements were made to better facilitate testing and user experience, including greatly improved file I/O, diagnostics and test operation. The Labview VI completely automates the 6 stages necessary to
conduct each test, which previously required manual operations during every test stage. The VI also runs two independent closed loop compensators to control flow rate and chamber pressure during each test. These control loops are implemented in linked sub-VI’s, enabling easier debugging and troubleshooting of control loop issues.

In Figure 6- File I/O Tab below, a File I/O Tab shows the file selection and preview tab of the main VI. Simple file browsing support for input and output paths, an automatic “.xls” file extension added to each output file and a live preview of the selected input file make test operation quick and efficient. Atmospheric and cigarette information can also be added in the VI for each test, which is then automatically appended to the output file.

![Figure 6: File I/O Tab](image)

Figure 6: File I/O Tab

Figure 7: Operation Tab shows the operation tab of the main VI. The only controls for running each test are a “Start Test” and “Stop Test” button. Diagnostic information regarding component states and a test stage indicator helps to diagnose any test issues and give a better overall impression of the operation methodology. Finally, a waveform chart is a prominent part of the operation tab, giving real-time results during the actual puffing stage. All three primary test parameters (Input Flow Rate, Measured Flow Rate, and Chamber Vacuum) are overlaid on one chart, enabling immediate cross comparison for investigative or diagnostic purposes.

![Figure 7: Operation Tab](image)

Project P12055: Electronic Cigarette Evaluation System
RESULTS AND DISCUSSION

In basic identification of system capabilities, small samples of tests were completed in order to characterize the capabilities of the system. In order to compare the revamped Phase II system with the previous Phase I system, a square wave step impulse was used as it maintain a comparison that can be used based on data acquired from Phase I testing. Seen below in Figure 8: System Characterization Test Results, a sample of the data used to characterize the system is shown.

![Figure 8: System Characterization Test Results](image)

The results indicate that the system closely replicated the input flow profile with a high degree of accuracy. In this case, the green line represents the input flow profile, and the red line represents the output flow profile that was actually recorded by the closed loop control system. The accuracy from this test was calculated to be less than 1 percent when comparing the actual volume flow with the total calculated input profile volume. The vacuum level, represented by the blue line, was also controlled very accurately due to the integration of the closed loop control. The vacuum level is controlled to within 3 inches of water (± 1.5 inches of water) of the desired set point. This represents greater control of the system, as well as proof that the automation introduced and implemented into the system provides more accurate results. The results were also found to be repeatable with expected amounts of error. It is to be noted that square wave profile provides a good characterization and a low amount of error, but as the system attempts to duplicate generic flow profiles, the repeatable amount of error increases to approximately 5%. This is a result of the increased complexity of the input flow profile which causes a decrease in the response time of the system due to higher demands on the system. Although there is an increase in error, it has presented itself to be systematic, which still allows for successful testing and collection of vapor emission from the electronic cigarette.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

In conclusion, the improvements made to the Electronic Cigarette Evaluation System can be considered a success as results met or exceeded the customer and engineering specification outlined in the design process. As with any scientific and engineering based research and development projects, there are areas for further consideration and research. The following areas have been identified as areas the advancements in the capabilities of the system can be achieved.

The first area identified for further research is the actual study of an electronic cigarette itself. The implications of how factors such as battery level, internal temperature, and airflow parameters affect the output of nicotine from the cigarette and subsequent deposition into human respiratory tracts have yet to be characterized. This can be achieved through further LabView implementations using specific voltage and pressure sensors that are retrofitted into the electrical system of an electronic cigarette, as well as into the ECES.

Additional improvements can be made to the flow control system as well. Three main areas exist for improvement; sensor noise reduction, better proportional valves and control optimization. The flow meter and
pressure sensor have significant noise thresholds within the range they are expected to operate. Labview filtering is currently used, and could potentially be improved, but an ideal solution would be a hardware filter designed for each sensor. Eliminating filtering from Labview would help improve operating speed and provide a better noise filter. The biggest current obstacle to profile reproduction is a time delay and positional hysteresis inherent in the proportional valves used. Both these factors lead to a much slower update rate than the rest of the system hardware makes possible, resulting in overshoot and generally poorer profile reproduction than could be achieved. Finally, the compensators used for both vacuum and flow rate control can be tuned more effectively. All parameters were tuned adequately, but better overall performance could likely be achieved with additional investigation.

REFERENCES


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