Mobile and Efficient Temperature and Humidity Control Chamber for Point-of-Care Diagnostics

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***Abstract*— Point-of-care (PoC) testing devices aim to bring affordable and convenient illness detection to resource limited locations. Our lab has developed a PoC tool that detects human papilloma virus (HPV) by applying lateral flow immunoassays and fluorescence detection. However, this device requires specified temperature and humidity settings to produce quick and reliable results. Therefore, when examining samples in the field, the need for a portable, climate-controlled chamber is prominent. By combining low cost electronics and household items, a simple feedback loop is designed to regulate the internal conditions of a potential testing environment. The ability of our chamber to maintain a desired climate will be tested for accuracy and stability to ensure that it is competent for in-field usage.**

~Index Terms: Point-of-care, climate chamber, portable, assay

I. Introduction

POC diagnostics are easily deployable devices that follow the ASSURED criteria (Affordable, Sensitive, Specific, User-friendly, Rapid and Robust, Equipment-free, Deliverable) making them ideal for impoverished areas where primary medical care is not available. With underdeveloped countries accounting for 95% of all deaths from infectious diseases, there is a clear need for accessible disease detection [1], [2]. By bringing PoC tools to these settings, individuals of all socioeconomic backgrounds may receive crucial health information that was previously unattainable. Our lab focuses on HPV as it accounts for over 70% of cervical cancer cases and is prevalent in low resource settings [3]. Specifically, the population of India has a severe issue with HPV causing it to be identified as a location of interest. Approximately 6.6% of women in India are harboring the virus at any given time. Cervical cancer, which develops from HPV, is the most common cancer found in women of India, accounting for 74,000 deaths annually [7]. Hence, our lab has chosen India for preliminary testing and development of our diagnostic tool.

The PoC device we created uses lateral flow immunoassays and fluorescence-based detection to identify HPV 16 and 18. However, the sensitive nitrocellulose substrate found on the assays requires a controlled climate for proper flow and reliable results. In order for medical professionals to offer on-site findings, an environmental chamber that can maintain a specified temperature and humidity is required. That way, testing boxes may be placed inside of the chamber at an optimal climate for the duration of the detection process. Though commercial climate chambers exist, they are expensive, immobile, and impractical for austere environments. So, the objective was established and the mission to develop a low-cost, transportable, and efficient chamber was underway.

To regulate the internal environment of our experimental chamber, we implemented a closed loop controller. A climate reading sensor was placed inside a conventional cooler and its data was interpreted by an inexpensive microcontroller [4], [8]. Because the chamber will be functioning in extremely scarce locations, a DC power supply is the most practical option. Thus, when considering the battery life of the source, efficiency is of great importance. By implementing a state machine to permit a microcontroller sleep mode, we predict the power consumption to diminish and the run-time of the chamber to be extended.

We have chosen a commercial cooler that has a built-in Peltier device which uses a difference in voltage to create a change in the internal temperature. Furthermore, a custom ultrasonic humidifier controls the moisture of the air contained. Though the two climate modifiers are cost efficient and low maintenance, we expect that it will be challenging to control the environment with precision. For instance, powering on the ultrasonic mist module for only seconds may drastically affect the climate. Preliminary testing of the functionality of the temperature and humidity controllers will be performed to get an idea of the devices' capabilities.

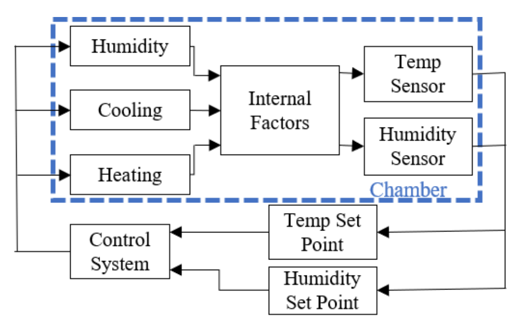

Figure 1. Sensor and microcontroller communication feedback loop for internal environment control

Our chamber was put through a series of tests to gather data regarding its precision, efficiency, and stability in realistic field scenarios. For example, the device must be capable of sustaining a specified climate when the lid is

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opened and closed multiple times. It is vital that our device demonstrates internal stability and accuracy over a range of external environmental conditions. In addition, the efficiency of the device is examined to ensure a stable setting may be maintained for the duration of the testing process. It is expected that a fully functioning temperature and humidity control chamber will be developed for in-field usage by the end of the REU program.

II. METHODS

A. Environmental Chamber Prototype Setup

Our feedback loop consists of a commercial sensor and microcontroller which regulate the internal environment of the chamber. The Adafruit BME680 sensor with humidity range 0-100% and temperature range -40-+130 °F was selected as the sensor, while the cost-effective Arduino MKR 1010 was chosen as the microcontroller [4], [8]. The electronics were placed inside of the purchased K-Box Electric Cooler with a built-in Peltier device. The installed thermoelectric tool consists of a junction between n and p-type conductors such that when current flows between, heat may be transferred from one side of the apparatus to the other creating a change in temperature [5]. With the flip of a switch on the outside of the chamber, heating or cooling can occur. Furthermore, a custom ultrasonic humidifier regulates the humidity of the air contained. The module holds a rapidly vibrating diaphragm which converts water into a light mist that is evenly distributed by a small computer fan [6]. Finally, a 12-volt battery was chosen as the power supply of the chamber due to its rugged and practical nature.

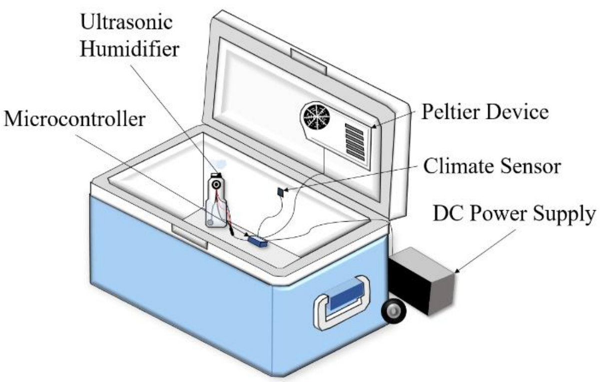

Figure 2. Labeled prototype of climate chamber powered by 12V DC source. Sensor and microcontroller communication control the internal environment with a Peltier device and ultrasonic humidifier.

B. Microcontroller State Machine

Efficiency must be considered because the chamber is powered by a DC battery source. In order to conserve power, a state machine for the microcontroller was implemented through programming. The code allows the Arduino to cycle from state to state, collecting, saving, and modifying the settings of the internal environment before returning to sleep. After an allotted sleep time, the microcontroller will re-initialize and cycle back through the capture, compare, and save data states.

C. Characterization of Climate Modifying Devices

Initial experiments are conducted to gather data regarding the functioning capabilities of the ultrasonic humidifier and built-in Peltier device. The two climate modifiers are operated individually and the environment inside of the cooler was recorded. The thermoelectric device's operating range was characterized by closing the lid of the chamber, pressing the cooling button, and allowing the temperature to saturate at a minimum over time. The same experiment was performed to test the Peltier's maximum heating option. Humidity was analyzed by sealing the chamber, turning the fan of the humidifier on, and recording the effect of the ultrasonic mist module. We are sure to note the effect of each device on both temperature and humidity as they may be interrelated.

D. Field Replication Experiments

We performed a series of experiments to replicate in-field usage of the climate control chamber. The cooler lid must be opened and closed in order to place samples in the testing boxes for analysis. Therefore, we will mimic the detection process by opening the lid for thirty seconds, closing the lid with the humidifier on for five seconds, then allowing the chamber to sit for another minute. The chamber's ability to maintain a specified climate will be evaluated by repeating this process several times and recording the status of the internal environment. Likewise, to replicate the box being used in India, we will evaluate the operating range of the Peltier device when the ambient temperature is 100 °F.

E. Environment Inside Chamber vs. Inside Box

This experiment allows us to conclude whether or not our chamber setup is sufficient for in-field usage. Because our PoC tool uses fluorescence-based detection, we have tried to prevent all outside light interference. Consequently, the detection sites are enclosed within a tight, black box. Yet, this design may prohibit the optimal testing climate from penetrating the walls of the testing box. To inspect this conjecture, one sensor was placed on the floor of the cooler and another was placed inside of the HPV testing device. A specified climate is achieved inside of the environmental chamber and the data from the two sensors were compared over time.

Figure 3. PoC HPV testing box that will be placed inside of the climate chamber for detection process.

III. Results and Discussion

First, the Peltier device is fully functioning and permitted a 30 °F swing for both heating and cooling when the ambient temperature was 77.8 °F. However, it takes approximately two hours for the temperature to saturate. This is not ideal for field scenarios when the internal environment is constantly affected by the opening and closing of the chamber lid. We will consider options to speed up stability and control so a set point temperature can be achieved more rapidly.

When further analyzing the sensor data, the coefficients of determination are 0.985 for heating and 0.975 for cooling with polynomial fits. This information can be used in the future to implement a controller to automate climate control. The sensor readings also show a significant inverse relationship between temperature and humidity with the Peltier device on. When temperature increases to 107 °F, humidity decreases 17% and when temperature decreases to 47°F, humidity increases 23%. This relationship is important to understand when attempting to reach a set point humidity as multiple factors must be put into consideration.

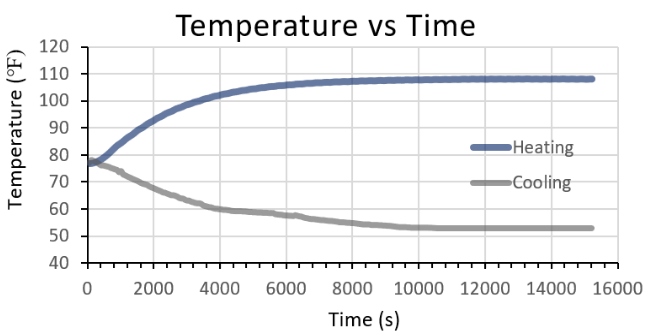

Figure 4. Sensor readings of temperature (°F) vs time (s) for characterization of built-in Peltier cooling (top) and heating (bottom) settings on commercial cooler.

The humidity control was analyzed by isolating the custom ultrasonic humidifier. When simply placing the humidifier into the enclosed chamber with the fan on, the humidity increased very slowly. Yet, when toggling on the ultrasonic mist module, the functioning capabilities of the humidifier were greatly improved. With an ambient humidity of 30.1%, the internal environment saturated at 95% in only 90 seconds. This is ideal for reaching a set point humidity quickly, yet precision is a concern. For instance, powering on the ultrasonic module for only seconds will drastically affect the humidity. This leaves little room for error in the time we leave the ultrasonic on because we have not implemented a device to dehumidify the enclosed environment. Also, we found that condensation is a concern because the sensor does not read properly when wet. Therefore, ideas for preventing overshooting must be considered.

Further characterizing the device, the coefficient of determination is 0.839 with a polynomial fit when the ultrasonic mist module is on. And, there is no measurable effect of the humidifier on the temperature of the internal environment.

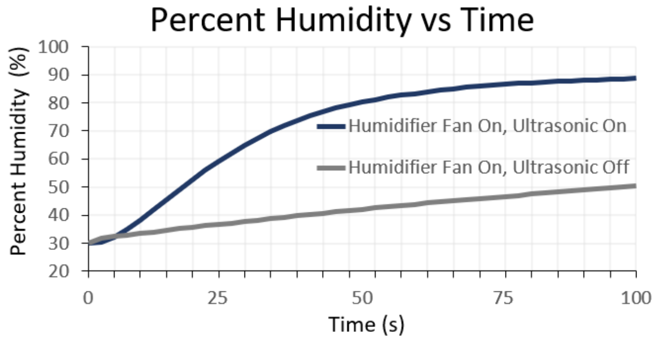

Figure 5. Sensor readings of percent humidity (%) vs time (s) for characterization of humidifier when ultrasonic mist module is on (top) and off (bottom).

Next, the chamber is analyzed in a realistic field scenario where the lid of the chamber is opened and closed over time. The sensor readings show a large spike in the humidity when the ultrasonic mist module is powered on for five seconds with lid closed at the 60 sec, 215 sec, and 370 sec marks. As shown, the chamber maintains most of the humidity for the following minute that the lid is left closed. This is ideal for the field because our chamber is able to quickly modify the humidity when samples are placed inside and maintain that environment for the duration of testing. However, as expected, the humidity easily escapes the chamber when the lid is left open for thirty seconds at the 125 sec, 280 sec, and 435 sec marks. This is not a concern for humidity control because the ultrasonic humidifier is quick to adjust, but the Peltier device is much slower to regulate. In addition, it is important to consider the relationship between the temperature and humidity as they are both affected when the Peltier device is on. The operating time of the humidifier may need to be adjusted to counteract the effects of the Peltier device.

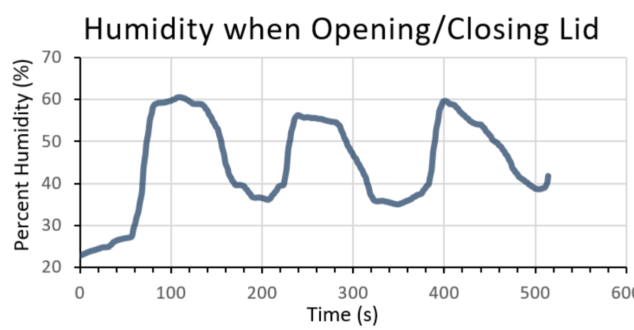

Figure 6. Sensor readings of percent humidity (%) vs time (s) for chamber when lid is opened and closed with humidifier on.

Finally, there is a significant difference between the environment inside the chamber and inside the PoC boxes. Since the testing devices are sealed containers, the modified climate has difficultly penetrating the outer surface of the box. When the ultrasonic humidifier is powered on for approximately six minutes, the sensor placed on the inner surface of the chamber saturates at 95% humidity. Yet, the sensor placed inside the testing box only reached 25% humidity. The same trend is expected when attempting to regulate temperature inside the boxes. This is not ideal because we have created the chamber to control the testing environment for the samples and speed up the detection process. With the current design, we have little to no control over the short-term climate in the boxes. Modifications to the testing boxes and designs will be considered in the future.

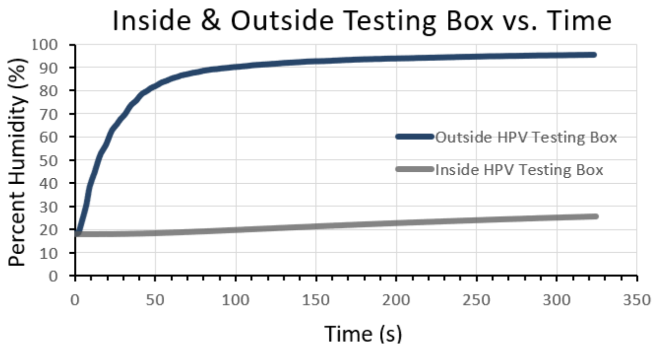

Figure 7. Readings of percent humidity (%) vs time (s) for two sensors in different locations. One is placed on the inner surface of the cooler (top) and saturates at 95% humidity, while the other is placed on the inside of the HPV testing box (bottom).

IV. Conclusion

In this paper, we demonstrated a functioning environmental chamber. We were able to apply sensor and microcontroller communication to gather climate data and modify the internal conditions of the cooler. We were also able to characterize the ultrasonic humidifier and Peltier device by analyzing their performances over time. By conducting small experiments, we were able to simulate field scenarios to gather data on the readiness of our control chamber. And, we recognized that the environment inside of the chamber and inside of the testing device did not align due to the tightly sealed outer box.

Altogether, the data showed that we are on a good track, but revealed the need for future modifications to our design. With the required updates, we believe that the chamber will be sufficient for on-site usage in India. This will allow the medical professionals to place testing boxes into a controlled environment where dependable results are produced. Then, the residents will be told with confidence whether or not they should seek out further medical attention based on the tests. By bringing our PoC detection tool and climate-controlled chamber to low resource locations, we hope to reduce the HPV infection in India and prevent cervical cancer cases from developing.

V. Future Investigations

Though the chamber is functional, we wish to plan the next steps to refine the design. Most importantly, we must implement a new strategy so that the climate within the chamber reaches the inside of the PoC testing devices more quickly. We have considered multiple blueprints such as feeding a tube from the chamber into the testing box or using a different material for the box itself.

Likewise, we wish to advance the environmental control from a manual to automated process. The characterization data for the climate controlling devices will be used to implement a bang-bang and PID controller. They will be programmed to find the error between the current and set point climates and respond accordingly. We predict that the PID controller will be capable of greater precision than the bang-bang's simple logic.

Finally, to experiment with improving temperature control and stability, a thermal mass will be introduced to the system. The metal block conducts very slowly, allowing it to store the desired temperature over time. Therefore, the block will maintain the temperature within its volume, even when the chamber lid is opened. This will assist the Peltier device in reaching the optimal climate more quickly when the lid closes.

Acknowledgments

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References

[1] Gubala, Vladimir, Harris, Leanne F. Ricco, Antonio J., Tan, Ming X., and Williams, David E. "Point of Care Diagnostics: Status and Future." *Analytical Chemistry 84* (2012): 487-515.

[2] P. Yager, G. J. Domingo, and J. Gerdes, "Point-of-care diagnostics for global health," Annu. Rev. Biomed. Eng., vol. 10, pp. 107–144, 2008.

[3] Ewaisha, R., I. Meshay, J. Resnik, B. A. Katchman and K. S. Anderson, "Programmable protein arrays for immunoprofiling hpv associated cancers", PROTEOMICS 8 (2016).

[4] Adafruit Industries, "Adafruit HTU21D-F Temperature & Humidity Sensor Breakout Board," *adafruit industries blog RSS*. [Online]. [Accessed: 06-Jun-2019].

[5] Francis J., Disalvo. "Thermoelectric Cooling and Power Generation." *Science 285.5428* (1999): 703-706.

[6] Ediger, Glen W., Israel, Gary P. "Ultrasonic Humidifier." Washington D.C: U.S. Patent and Trademark Office. (2013)

[7] Kaarthigeyan, K. "Cervical cancer in India and HPV vaccination." *Indian Society of Medical & Paediatric Oncology* vol. 33, 2012.

[8] "MKRWiFi1010," *Arduino*. [Online]. Available: https://www.arduino.cc/en/Guide/MKRWiFi1010. [Accessed: 13-Jul-2019].