International Journal of Technology 10(8): 1626-1634
ISSN 2086-9614

FABRICATION AND CHARACTERIZATION OF AN AFFORDABLE CONDITIONED BIO-SPECIMEN TRANSPORTER (CONBIPORT) FOR URBAN AREAS

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(Received: May 2019 / Revised: August 2019 / Accepted: November 2019)

ABSTRACT

Many biological and biomedical laboratories in the Greater Jakarta have limited facilities. Problems arise when bio-specimen transports are moved from one laboratory to another. These transports may take hours due to traffic in the Greater Jakarta area. Lengthy transport may be problematic to the research at-hand, since many biological specimens will fail to survive if temperatures exceed 37°C for even a few minutes. When this happens, the condition of the specimen may be compromised or even damaged. To address this problem, we fabricated and tested a conditioned bio-specimen transporter (Conbiport). The Conbiport used a Rubbermaid cooler box as a basis, which is made of high-density polyethylene (HDPE), allowing for temperature preservation. The Conbiport was equipped with an Arduino microcontroller, a heater, a temperature sensor, and its peripheral components so that the temperature inside the Conbiport could be steadily maintained. Four different control system configurations were tested: proportional (P-dom), proportional-derivative (PD-dom), proportional-integral-derivative (PID) and on-off. The results showed that the P-dom configuration exhibited the fastest heat rate. This configuration may provide better portability when it comes to specimen testing, despite the tendency of the temperature to offset from the setpoint. On the other hand, the PID controller provided the most stable temperature preservation, although it took a longer time to achieve the setpoint. Nonetheless, we proved that the Conbiport could maintain the temperature required for specimen transportation in urban areas, such as Greater Jakarta.

Keywords: Bio-specimen; Conbiport; Control; PID; Transporter

1. INTRODUCTION

Indonesia lacks important medical facilities (Elfani & Putra, 2013), which includes facilities in.

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Permalink/DOI: https://doi.org/10.14716/ijtech.v10i8.3523

(bio) medical laboratories such as testing instruments. As a result, some specimen testing processes must be performed in laboratories that are more fully equipped.

However, such laboratories do not exist in every region of Greater Jakarta. These types of laboratories are mainly located along main roads. This means that some specimens may be transported over up to 10 kilometers. In this case, depending on the traffic, specimen transports can take hours to arrive at their destination. In Greater Jakarta, traffic jams have been a daily occurrence for the citizens (Lee, 2015). At times, it may take up to an hour to move just 1 kilometer. Due to these traffic jams, some people called Jakarta an urban nightmare (Steinberg, 2007).

Traffic jams pose a problem to the bio-specimen transport, which requires a specific environment to grow and live. For instance, some biological specimens required a temperature of approximately 37°C to maintain their viability and growth in a bioreactor (Whulanza et al., 2014; Whulanza et al., 2017) or an organ model (Sagita et al., 2018). A failure to maintain the required temperature might damage the bio-specimens (Chen et al., 2015). Studies from Whulanza et al. (2016) and Nadhif et al. (2017) shows, in the first study, *Candida albicans*—biofilm-forming fungi in the oral cavity)—was cultured on a modified polydimethylsiloxane (PDMS) membrane. In the latter study, *Candida albicans* was cultured in the lab-on-chip channels. To qualitatively confirm the existence of the fungal colonies in the two studies, scanning electron microscopy (SEM) was required. Unfortunately, the SEM imaging could only be performed at another lab since the tool was not available since the tool was not available at the initial lab. Therefore, the specimens were transported to the SEM facility, which took 1 to 1.5 hours. Unfortunately, the air temperature outside was significantly different from the desired temperature for cells to survive (Gow et al., 2012), which led to the destruction of the specimen (Siswanto et al., 2016).

To tackle the aforementioned problem, an assistive device is required to maintain the specimen at an ideal temperature. One of the most feasible approaches is using a portable incubator (Byrd et al., 1997; Suzuki et al., 1999; Varisanga et al., 2002). Unfortunately, all commercial portable incubators for microbiology and tissue engineering research in Indonesia are imported, leading them to be relatively expensive (reaching approximately US$ 1,300). The purchasing of this type of incubators may consume around 18–60% of the grant received by the researchers. This problem inspired us to design an affordable conditioned bio-specimen transporter (Conbiport), which uses simpler technology and lower-cost materials. Therefore, bio-specimen transport in urban areas, like Greater Jakarta, can be safeguarded.

2. METHODS

2.1. Hardware Configuration

We designed a conditioned bio-specimen transporter (Conbiport) using a Rubbermaid cooler box as the basis. It had an inner length, width, and height of 26 cm, 16 cm, and 20 cm, respectively. The cooler box was made of high-density polyethylene (HDPE), thus allowing for temperature preservation (Elias, 2005). The box provided a sufficient space to fit an Arduino microcontroller unit, a battery, a heater, a DHT temperature sensor, and other complementary components, as can be seen in Figure 1. An Arduino microcontroller unit and its necessary peripherals were used to ensure stable temperature preservation within the box during the transport (Figure 1.e). Arduino has been used in medical devices, such a detection system for heart disorders (Hugeng & Kurniawan, 2016). Furthermore, the DC current to the device was regulated using a relay (Figure 1.c). A battery (Figure 1.a), which consumed a relatively large volume, was laid on the rear side of the box. A heater (Figure 1.d) was placed on the left side of the active space for bio-specimens (Figure 1.f) so that the heat could be transferred more efficiently to the specimen. A DHT11 temperature sensor (Figure 1.b) was placed in the middle of the box to ease the wiring and allow for more ergonomic handling of the specimen in and out of the incubator. The acrylic walls were designated to separate each section of the Conbiport. Furthermore, the walls are used to mount an Arduino microcontroller, a relay, a heater, and a DHT11 sensor.

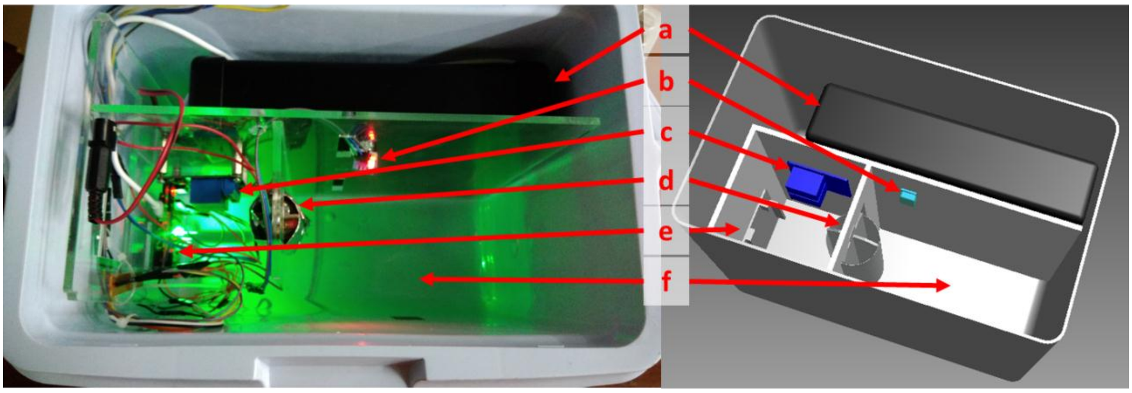

Figure 1 Inner view of the Conbiport (left: real photograph, right: 3D modeling) with all its components: a battery (a), a DHT11 sensor (b), a relay (c), a heater (d), an Arduino board (e), an active space for the bio-specimens (f), and other electronic peripherals

To maintain the performance of the Conbiport during transportation, a Vivan BB64 62400 mAh super-capacity battery was used. The battery supplied power to the Arduino and a heater—which were connected in parallel—through a relay. We used a DC power output of 100 Watt (13,3 V) with an expectation that the Conbiport would reach the desired temperature in a short period of time.

2.2. Heat Rise Simulation

Before the test, the heat transfer inside the active part of Conbiport (Figure 1.d) was simulated using COMSOL Multiphysics software (Hawachi et al., 2014). Therefore, the heat rise in the active space was predicted. The active space had a dimension of 9 cm × 16 cm × 16 cm. The side—where the heater was placed—and the backside were made of polymethylmethacrylate (PMMA), as the material was used as a separation wall. Meanwhile, the right and the front side were the wall of the Rubbermaid box, made of HDPE. The heater was set as an aluminum plate, modeling the real heater, which was covered with aluminum foil. The power supplied to the heater was set to 100 W. The virtual temperature probe was placed in the middle of the active space as a double stack of multi-well plates.

2.3. Control System Configuration

To measure the real-time temperature inside the Conbiport, a DHT11 temperature sensor was connected to an Arduino microcontroller. The sensor had an 8-bit resolution, which translated to a temperature of 1°C and a sampling rate of 1 Hz. In this experiment, we set the temperature in the Conbiport at 38°C. The Arduino used temperature data to control the relay, forming a closed loop proportional-integral-derivative (PID) control system (presented in Figure 2.a) (Kiam et al., 2005). The PID control system supplied the relay with a result of the error function with different gains for each denominator or the so-called pulse width modulation (PWM). The error values from all denominators combined so that the PWM signal had a value between 0 and 255. If the error was high, the value of the signal increased. Four gain configurations were used in this experiment to determine the desirable performance for this device, including rapid heating to a set temperature and stability during temperature preservation. In the first configuration, we only used a proportional controller (P-dom), while the integral (I) and derivative (D) were switched off. In the second configuration, we used PD controller (PD-dom). The third configuration was the PID controller. Meanwhile, the fourth configuration was an on-off system. In this configuration, the relay was turned on (PWM signal = 255) as long as it had not reached the setpoint. On the other hand, when it reached the setpoint, the relay was switched off (PWM signal = 0). When the temperature went down, the relay was automatically turned on, and so on until it reached stability. We performed the experiment for 2 hours starting from the ambient temperature (29°C), following the real application of the Conbiport.

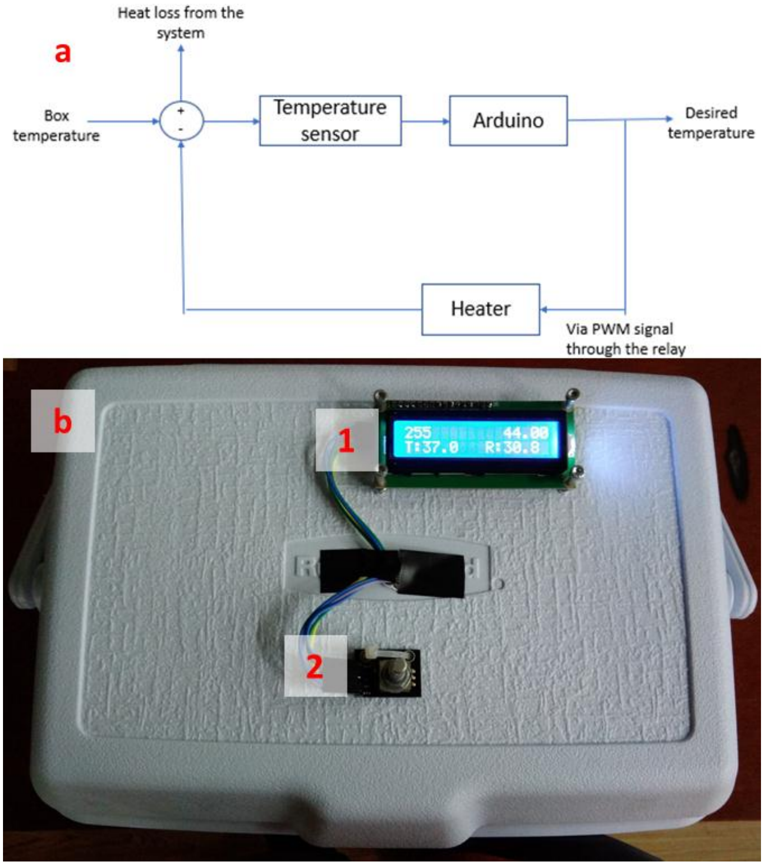

Figure 2 Block diagram of the Conbiport system (a) and the lid of Conbiport with: (1) an LCD; and (2) a rotary control

2.4. Data Acquisition

The Conbiport was equipped with a liquid crystal display (LCD) (Figure 2.b.1) and a rotary control (Figure 2.b.2) attached to the lid of the Conbiport. The upper left side of the LCD showed the real-time PWM signal transferred to the Conbiport, while the upper right side showed the relative humidity inside the Conbiport. The bottom left side of the LCD showed the desired temperature, adjusted by the rotary control. Meanwhile, the bottom right side showed the real-time temperature inside the Conbiport. The placement of the LCD and the rotary control on the lid of the Conbiport allowed users to observe and set the desired temperature directly without tinkering with the programming. During the test, the Arduino was connected to a personal computer (PC). A Parallax Data Acquisition tool (PLX-DAQ) software add-in for Microsoft Excel was used to show and record the real-time temperature. The data acquisition was performed with four different control system configurations, as previously mentioned. Data acquisition stopped when the temperature acquired two oscillation periods during the temperature preservation. This decision was made because we wanted to see the amplitude and the frequency of the oscillation. Finally, we used a Microsoft Excel 365 software to post-process the collected data to compare all the control system modes.

2.5. Data Analysis

After all the data were acquired, the heat rise from the simulation was presented and compared with the measurement results. Moreover, data from the four different configurations were compared, in terms of heat rise and oscillation characteristics. The most desired configuration could be determined accordingly.

3. RESULTS AND DISCUSSION

3.1. Heat Rise Simulation

The power supplied to the heater was at its maximum (100 W), reconstructing the on-off configuration. As a result, the middle section of the active part reached the set temperature (38°C) at minute 18.

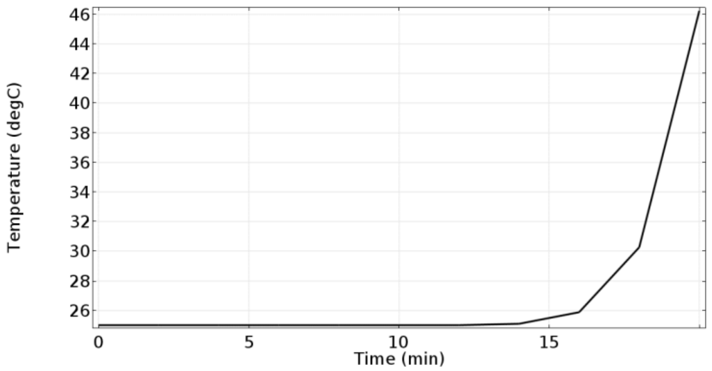

Figure 3 Graphical plot of simulated temperature gradient at the active space

3.2. Heat Rise Measurement

The four configurations reached the set temperature with different heat rise behaviors (Figure 4). The on-off configuration reached setpoint after 38 minutes. The P-dom and PD-dom configurations reached the set temperature at almost the same time, minute 32 and 33, respectively, which were faster than the two other configurations. The fast rising time from the two configurations was the effect of the gain in the proportional control, which resulted in a rapid rise in temperature. Therefore, both P-dom and PD-dom had faster rising times. Meanwhile, the PID controller had the slowest heat rate, taking 50 minutes to rise. The lowest heat rate in the PID controller confirmed previously-held knowledge about the controller, in which the proportional gain (K_p) decreases.

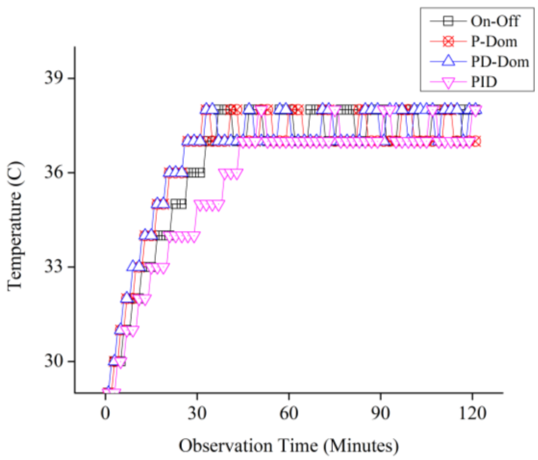

Figure 4 Result plots from the four different configurations near the setpoint temperature (38°C)

Unsurprisingly, the rising time for all configurations was longer than the rising time in the simulation. First, the simulation was designed in an isolated system, while in the real device, the active space was not tightly enclosed within the PMMA and HDPE walls. Rather, there were openings between the walls. In the simulation, there was even an air gap between the heater and the PMMA wall (Figure 1.d). The openings and the air gap caused heat loss from the active space to the other compartments, extending the rise time. Second, in the simulation the heater was set as an ideal aluminum plate, thereby accelerating the rate of the heat transfer. Meanwhile, in the real device, the aluminum in the form of foil was only used as a cover for the heater, which had a more complex structure.

In terms of time efficiency, the P-dom was preferable since it generated the fastest rising time to reach the setpoint, allowing for faster preparation before the specimen transport. Conversely, due to the lowest rising time of the PID controller, the user may require the longest preparation time before using the Conbiport. One possible way to rectify this issue is to supply a higher power to the heater. However, a higher power requires a better wiring quality. Therefore, we opted to only supply the heater with a power of 100 Watt. Moreover, using a higher power may increase the temperature of the heater surface. This could damage bio-specimens should they touch the heater.

3.3. Oscillation Characteristics

All four control system configuration tests showed that the Conbiport was able to achieve and maintain thermal preservation. The top, middle top, middle bottom, and bottom plots present the testing results from the on-off, P-dom, PD-dom, and PID controller, respectively (Figure 5).

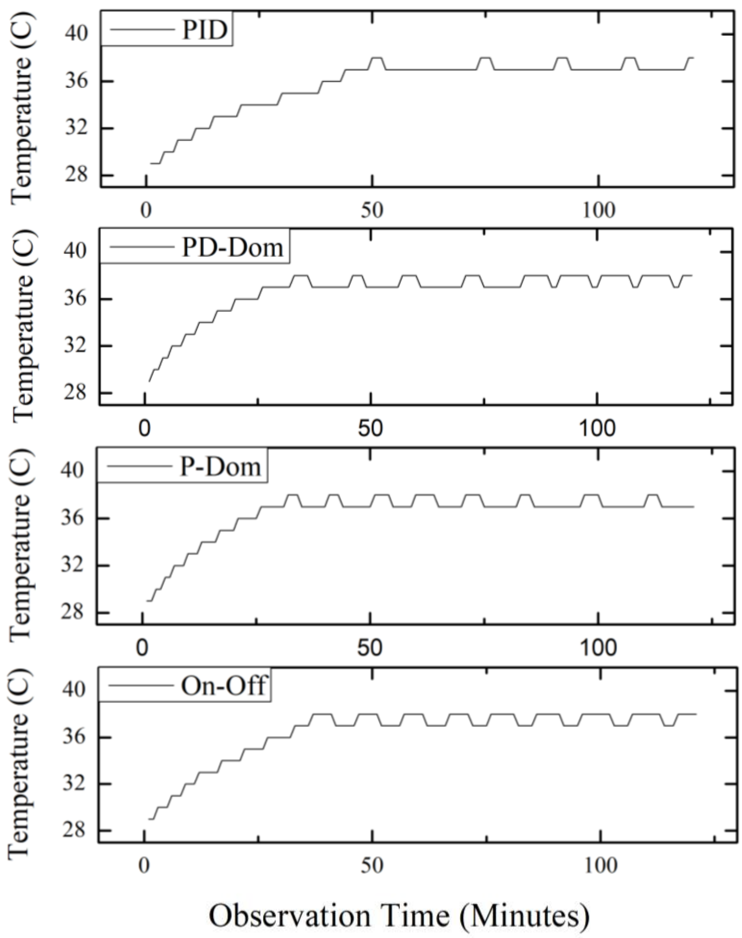

Figure 5 Result plots from the four different configurations

Each plot presents post-processed data after 2 hours of testing with a sampling rate of 1 Hz. All data were rounded down to the nearest integer. Oscillation occurred due to the control system mechanism that increased and decreased the temperature transferred by the heater to achieve and maintain the specimens' temperature at setpoint. In general, the oscillation characteristics looked similar to sinusoidal waves.

In general, all the configurations showed the same oscillating amplitude (0.5°C), with a range from 37°C to 38°C. The results were positive given the narrow range in temperature. Subsequently, oscillating characteristics for each configuration were observed to determine the configuration with the best temperature stability summarized in Table 1. The on-off configuration showed the most consistent oscillations regarding the length of peaks and hills, with an average frequency of 1.67 mHz. Consistent oscillations are understandable as there was no gain involved from the P, I, or D controller.

On the other hand, both the P-dom and PD-dom had variative oscillation patterns. The frequency for the P-dom decreased over time from an initial frequency of 1.85 mHz to 1.19 mHz in the end ($f_{average}$ = 1.48 mHz). Furthermore, the configuration preserved the temperature mostly at 37°C. This result confirmed the inherent problem of the P-dom, the steady state error or offset, which manifested in a 1°C decrease from the setpoint temperature. Meanwhile, the frequency of the PD-dom increased from 1.28 mHz to 1.85mHz ($f_{average}$ = 1.64 mHz). In the beginning, the temperature mostly stayed at 37°C, while after minute 83 the temperature mostly remained at 38°C. This result also confirmed the presence of the PD-dom with the offset and steady state error after minute 83. Using a sampling rate of 1 Hz, the observed offset reached a temperature of 38.5°C.

The PID controller presented its own unique behavior. The temperature stayed stable at 37°C with occasional spikes of 1°C for 3 minutes before returning to 37°C. The average frequency for this configuration was 0.95 mHz, with an initial and final frequency of 0.69 mHz and 1.19 mHz. The results confirmed the prior knowledge regarding the fast settling time for the PID controller.

Table 1 Summary of the characterizations for each configuration

	Configuration			
	On-Off	P-dom	PD-dom	PID
Average frequency (mHz)	1.67	1.48	1.64	0.95
Amplitude (°C)	0.50	0.50	0.50	0.50

After testing all the configurations, the PID controller showed the most optimal functionality. The PID controller stably maintained a temperature inside the Conbiport at 37°C, the temperature desired by bio-specimens to live. The P-controller, on the other hand, generated the fastest rising time. Unlike the other three configurations, the on-off configuration provided the most consistent oscillation.

4. CONCLUSION

We successfully fabricated and tested an affordable conditioned bio-specimen transporter (Conbiport). All the components of the Conbiport worked as intended. The Conbiport was able to perform thermal preservation for 120 minutes with the installed battery. Four distinct control system configurations were tested, in terms of heat rise and oscillation behavior. The P-dom presented the fastest heat rate. This configuration is very suitable for a user who requires the fast mobility of specimens for testing. Nonetheless, this configuration is prone to an offset. On the other hand, the PID controller was the most stable of all the configurations, making it the most preferable configuration. To cope with the slow heat rise, the Conbiport must be prepared for 50 minutes prior to specimen transports. According to the results described in this paper, the Conbiport can be a reliable medium to transport bio-specimens in urban areas.

5. ACKNOWLEDGEMENT

This article's publication is supported by LPDP *Rispro Invitasi* 2019 under contract number KEP-52/LPDP/2019.

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