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DESIGN, FABRICATION AND TESTING OF A LAB-SCALE HYBRID MOBILE COOLING SYSTEM FOR OYSTER INDUSTRY

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ABSTRACT

Cooling system is critical to maintain freshness of oysters and avoid contamination by bacteria. However, there is no persistent and efficient temperature control mechanism for cooling and storing of oysters in its supply chain from oyster farmer to the end consumers (e.g., market, restaurants). The aim of this project is to design, fabricate, and evaluate a lab-scale hybrid mobile cooling system for oyster aquaculture. This innovative hybrid cooling system integrated 110 volts AC cooling unit and 12 volts DC cooling unit with six individual chambers. These special features it to work under different power source. Even after power off, it can still run for several hours with battery (i.e., outage). So, it can be moved from boat to customers without change the storage condition of oysters. Six individual chambers have a potential to reduce energy loss and improve cooling performance because removing oyster baskets from one chamber will not affect temperatures in the other chambers. In this study, cooling system was fabricated in the laboratory based on the 2D design and 3D model. The performance of this cooling system was tested under various air circulation conditions (e.g., no vent open, two vents open, two vents open and air circulation fan on). Both cooling speed and the stand deviation of chamber temperature were used to evaluate the system cooling performance. Results indicated that the additional of air fan and two open vents in the divider has better cooling performance than the other two operating conditions. Hybrid cooling system with two vents and air circulation fan on can effectively cool down the oyster temperature from 21.1 ° C to 5.6 ° C within three hours. The stand deviation of the temperatures in six individual chambers can be reduced to 0.83 ° C in four hours.

Keywords: oyster aquaculture, hybrid mobile cooling system, air circulation, solar energy, thermal uniformity

1. INTRODUCTION

The Chesapeake Bay is famous for its oysters and oysters also play a vital role in the Bay ecosystem (Greenberg, 2012). The oyster industry has contributed millions of dollars to the region's economy since late nineteenth. However, oyster harvests of Chesapeake in 2008 declined to less than 2% of the historical peak in 1880 (Pelton, 2010). According to the conclusion of Rothschild et al. (1994), a century's overfishing is the key factor to the declination of oyster population. In 2009, Maryland's Oyster Restoration and Aquaculture Development Plan was announced that Maryland is trying to gradually shift oyster business from a fishing model to a farming model. According to the recent report of The Baltimore Sun, sales of farmed oysters jumped form 3,300 bushels in 2012 to more than 74,000 bushels in 2017, which making oyster aquaculture a roughly $5 million industry in Maryland (Dance, 2019). Oysters are usually sold and consumed alive. It may be stored for several weeks before consumption. However, the long storage time without appropriate cooling process might bring the risk of spoiling (Aaraas et al., 2004). For example, Vibrio parahaemolyticus (Vp) and Vibrio vulnificus (Vv) are associated with the consumption of raw oysters (Cole, 2015). From 1981-1992, seventy-two cases of Vv infection from raw oysters were reported and 36 (50%) patients died in Florida (Hlady et al., 1993). It has been proven that Vp levels significantly increase (p-value <0.05) over time with the storage temperatures (Mudoh et al., 2014). So that, regulations require oysters to be cooled and refrigerated after harvest in many countries. For example, Australian Shellfish Quality Assurance program requires oyster intended for consumption as raw product should be placed under ambient refrigeration at 10°C or less within twenty-four hours of being harvested (Australian Shellfish Quality Assurance Advisory Committee, 2009). According to Code of Maryland Regulations for Vp Control, the internal temperature of oysters should reach 10°C or below within 10 hours or less after being placed under temperature control from June 1 through September 30.

Madigan evaluated one of Australian oyster cool chain from Smoky Bay, South Australia to the Sunshine Coast. He found that the ideal storage temperature all through the cool chain is not easy to achieve. As shown in Figure 1, oyster did not cool down to 10°C around 30 hours after harvest while the ambient temperature varies frequently from below 0°C to above 20°C (2008). Ice was widely used as cooling medium in the traditional boat cooling systems. However, it is not an ideal option for long time storage and long-distance transportation of oyster since ice will melt. There are different kind of on boat mechanical refrigerating system exists today (Dellacasa, 1987). However, its working ability is restricted by the horsepower of fishing boat and required large power consumption (Wang, 2005). Despite the fast development of refrigerate industry since its invention, there is no mobile cooling system specially designed for oyster industry on market.

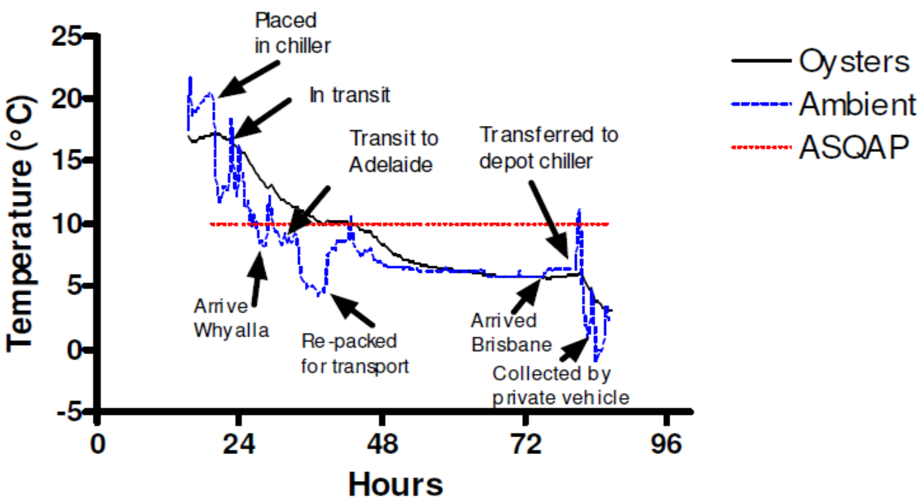

Figure 1: Temperature Profile of Oysters during Transportation (Madigan, 2008)

Solar energy is the cleanest and most abundant renewable energy source. A solar electric refrigeration system consists mainly of photovoltaic panels and an electrical refrigeration device. The biggest advantage of using solar panels for refrigeration is the simple construction, mobile, and high overall efficiency. As shown in Figure 2, a schematic diagram of a solar electric compressor air system is given (Kim and Ferreira, 2008). Torres-Toledo et al. (2016) built a solar icemaker and found that the icemaker can deliver the target ice production for 89% of the days of a typical year at the selected location. Zhang et al. (2010) developed and conducted performance test of photovoltaic-powered refrigerator in different climate zones. Experimental results indicated that the refrigerator could work well in Shanghai area and has a stable performance in other different climatic regions. The above papers showed that solar energy is one of potential energy resources for refrigeration system.

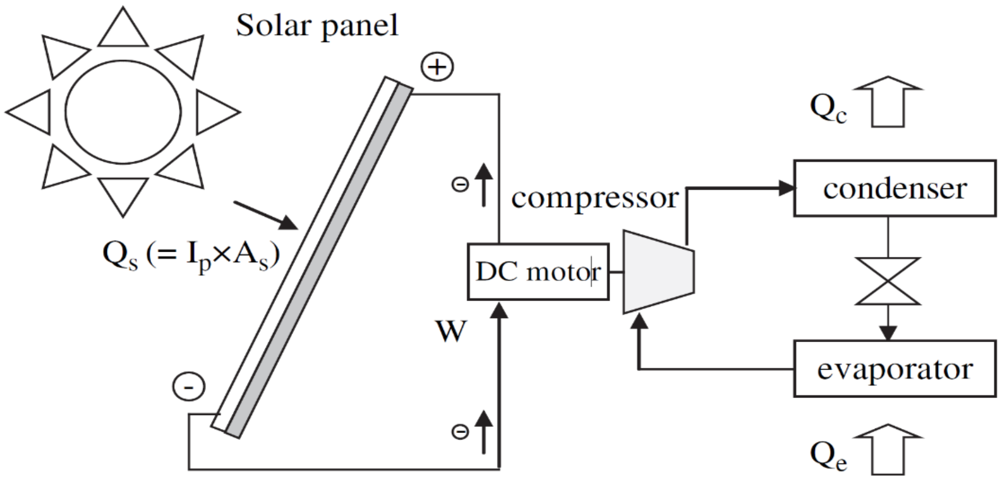

Figure 2: Schematic Diagram of Solar Electric Compression Air-conditioner

There are two technical challenges during oyster cooling. Firstly, rapid cooling is required to keep oyster fresh as the legal obligation. Secondly, even if the average temperature inside the refrigerator cabinet is adequate, local rise in temperature may damage oyster freshness. Thus, rapid cooling, thermal uniformity, and lower temperature variation inside the chambers of cooling system are required to keep oyster fresh (Fukuyo, 2003). Ding et al. (2004) found that the clearance between shelves and back wall as well as doors are important to reduce temperature variation and achieve uniform temperature distributions. In addition, a disturbing axial fan and an air duct were found to improve airfield and temperature uniformity in a refrigerator.

In summary, the current cooling system is not appropriate to provide ideal storage temperature of 10°C within specific cooling time required by law (10 hours or less). Solar energy is one of the best options to support a sustainable and energy efficient mobile cooling system. In addition, air circulation strategies can be used to reduce cooling time and improve thermal uniformity in a cooling system. The objective of this study is to develop, fabricate and evaluate a hybrid mobile cooling system which integrated 110 volts AC cooling unit and 12 volts DC cooling unit. Temperature changes within six individual chambers and cooling time of mobile cooling system were measured under various working conditions. It is believed that the hybrid mobile cooling system, which can move from boat, truck to final customer without any change of oyster storage condition will benefit the Chesapeake Bay oyster farmer.

2. METHODOLOGY

2.1 Effects of 4th IR on Education

The lab-scale hybrid mobile cooling system with two cooling units, 110 volts AC and 12 volts DC were designed and fabricated for the oyster farmers in the Center for Advanced Energy Systems and Environmental Control Technologies at Morgan State University. As shown in Figure 3, the frame of the cooling system was built from a heavy-duty shelf steel shelving material. The exterior wall was made from polystyrene foam board (R-value 10), plus double bubble insulation reflective roll insulation (R-value 3). The 110 Volts AC cooling unit and 12 Volts DC cooling unit were installed and top mounted.

Figure 3: Raw Materials and Cooling Components for the Mobile Cooling System

As shown in Figure 4, a divider was vertically erected in the middle of the frame, which divided whole inner space into two sections. Each section is horizontally divided into three chambers by wire decking, the wire-mesh design can allow good air circulation while offering strong support. Thus, six individual chambers of cooling system, named from chamber 1 to chamber 6 individually. Chamber 1-3 belong to the left section and chamber 4-6 belong to the right section. Left section is operating with 110 volts AC cooling unit and forced convection air while right section is running with 12 volts DC cooling unit with natural convection air circulation. A DC battery was attached with this system to make sure the system can keep working even without energy source for a period. The clearance between the shelves and door was reduced to 0.5 inch to achieve uniform temperature distribution. Two vents, which can be open and close, was assembled at the top and bottom of the divider. The AC Infinity AIRTAP T4, Booster Fan can be mounted on the vent to offer air circulation. The ventilation system (vents and fan) was designed to ensure air circulation between two sections.

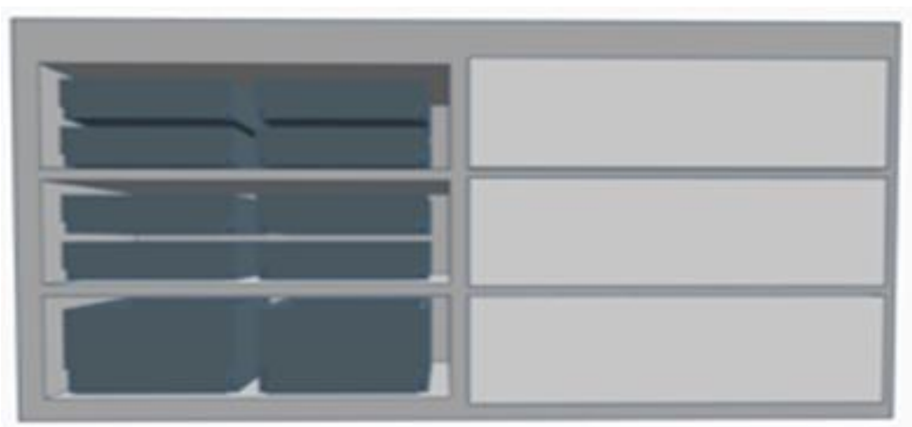

Figure 4: 3D Model of Mobile Cooling System with Two Sections and Six Chambers

2.2 Experimental Conditions and Instrumentations

In order to simulate the real oyster cooling process in the lab-scale hybrid mobile cooling system, oyster shell and equal amount of water was used to replace the missing oyster meat of the shell are used in this experiment. Table 1 indicates the weight of shells (in kg.) and water (in kg) in each chamber. The total amount of 95.2 kg of oyster shell plus 10 kg of water was put into the cooling system. Six set of Channel K Type Digital Thermometer were used to detect the temperatures of oyster in the center of each basket and ambient temperature in each chamber. The oyster temperature of each basket was recorded every 20 minutes. Temperature between 2 and 4 °C is the ideal storage condition for oyster. Thus, the desired cooling temperature in cooling system is set at 2 °C during this experiment. Cooling system performance include the cooling speed and temperature distribution were evaluated under three different operating conditions: working independently (two vents are closed); two vents open for air circulation between two units; two vents are opened and circulation fan on to strengthen the cooling air circulation.

Table 1 Distribution of Oyster Shell and Water in the Cooling System

110 Volt Unit (Left Section)		12 Volt Unit (Right Section)	
Chamber 1 (kg)		Chamber 4 (kg)	
4.76 shell+0.5 water	4.76 shell+0.5 water	4.76 shell+0.5 water	4.76 shell+0.5 water
Total: 21 shell+1 water		Total: 21 shell+ 1 water	
Chamber 2 (kg)		Chamber 5 (kg)	
9.52 shell+1 water	9.52 shell+1 water	9.52 shell+1 water	9.52 shell+1 water
Total: 42 shell+2 water		Total: 42 shell+2 water	
Chamber 3 (kg)		Chamber 6 (kg)	
4.76 shell+0.5 water	4.76 shell+0.5 water	4.76 shell+0.5 water	4.76 shell+0.5 water
4.76 shell+0.5 water	4.76 shell+0.5 water	4.76 shell+0.5 water	4.76 shell+0.5 water
Total: 47.6 shell+2 water		Total: 47.6 shell+2 water	

3. RESULTS AND DISCUSSION

Performance analysis of 110 Volt and 12 Volt cooling units working independently without and with load were performed and compared. Working independently means vents are closed while air circulation fan was off. In this experiment, it was assumed that two system were working independently because there is no vent between two sections. Figure 6 summarized the minimum, average and maximum temperature in the 110 volts and 12 volts sections without load. Results indicated that the temperature in the 110 volts section decreased from 21°C to 3.4 °C. While the temperature in the 12 volts section decreased from 20.6°C to 9.7°C within 5 hours cooling time. Figure 7 summarized the minimum, average and maximum temperature in the 110 volts and 12 volts sections with load. Results indicated that the temperature in the 110 volts section decreased from 20.8°C to 5.5°C while the temperature in the 12 volts section decreased from 20.8°C to 12.8°C within 7 hours cooling time. It can be seen that the cooling time was increased by the addition of cooling load. It was also found that 110 volts section has a better cooling performance than 12 volts section and air circulation may be required between two sections to achieve temperature uniformity.

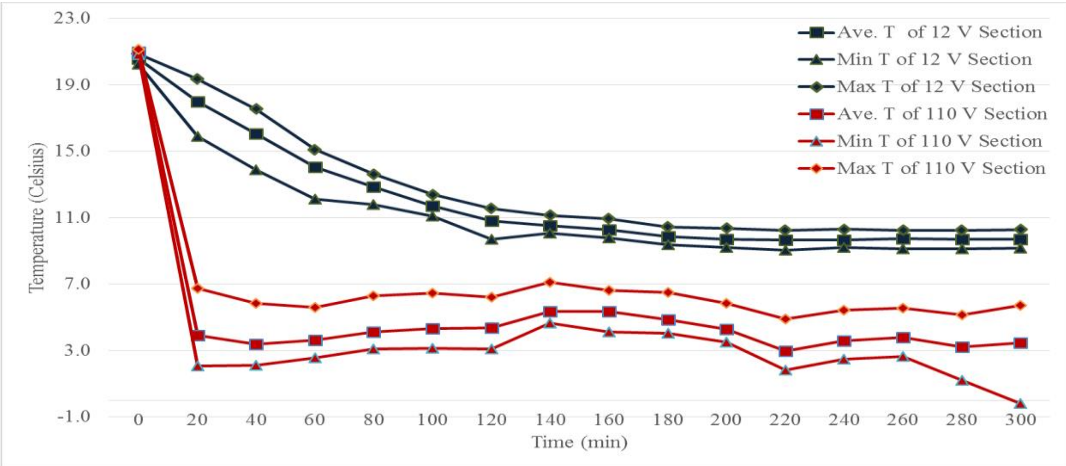

Figure 6: Cooling Speed and Minimum Average and Maximum Temperature without Load

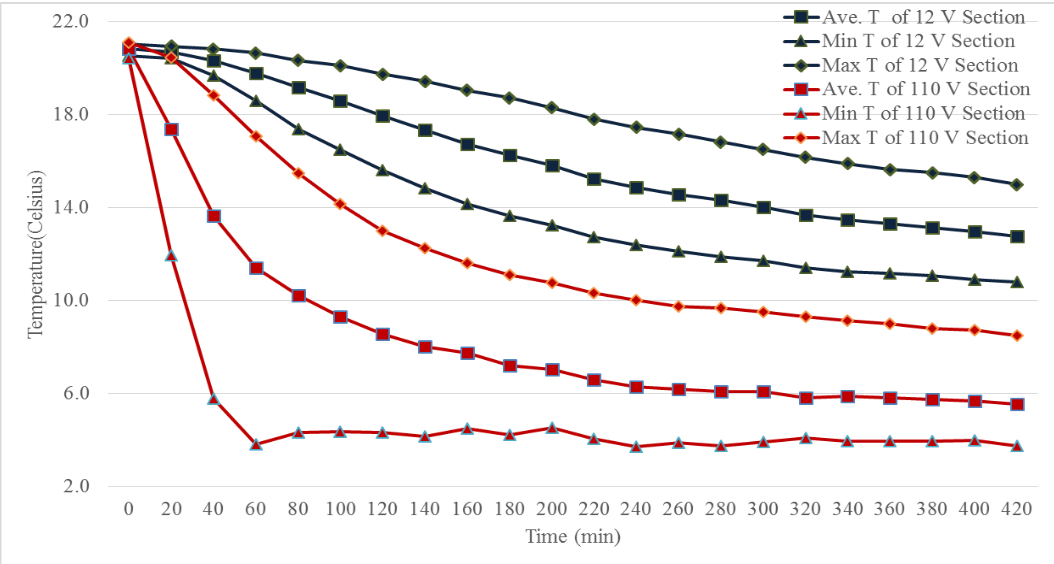

Figure 7: Cooling Speed and Minimum Average and Maximum Temperature with Load

Performance analysis of 110 Volt and 12 Volt units working with two vents open with load were further performed to improve the temperature uniformity. Two vents in the divider were expected to improve the air circulation and cooling performance. Figure 8 summarized the minimum, average and maximum temperature in the 110 volts and 12 volts sections. Results indicated that the temperature in the 110 volts section decreased from 20.9°C to 4.4°C while the temperature in the 12 volts section decreased from 20.8°C to 10.5°C within 7 hours. Compared with cooling performance on Figure 7, the cooling performance was improved by 1.2°C and 2.3°C in 110 volts and 12 volts chamber, respectively.

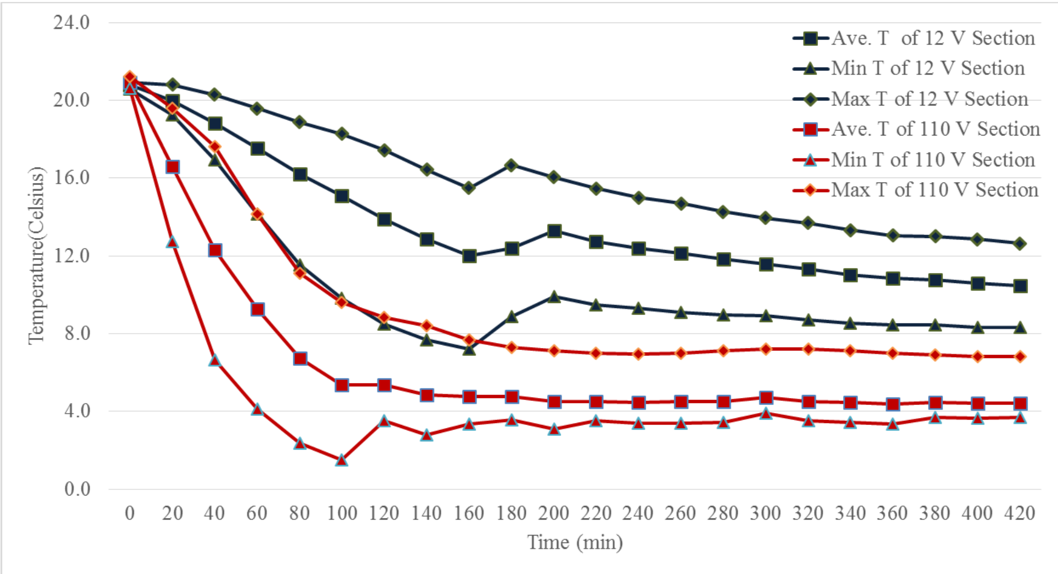

Figure 8: Cooling Speed and Temperature with Load and Vents Open

Under the condition of two vents open and circulation fan on, cooling performance of hybrid mobile cooling system were analysed. The cooling speed and temperature changes in the two chambers are recorded and summarized in Figure 9. It was found that average temperature of 12 volts chamber was decreased about 12.1°C within 280 minutes. However, the average temperature of 12 volts chamber in case of no vent has dropped 8°C within 7 hrs and while the case of two vents has dropped 10.3°C within 7 hrs. It was proved that there is significant improvement in both cooling speed and temperature uniformity for the hybrid mobile cooling system by adding the ventilation system (vents and fan). These results showed the importance of air circulation in the cooling system and necessary of future study on this area.

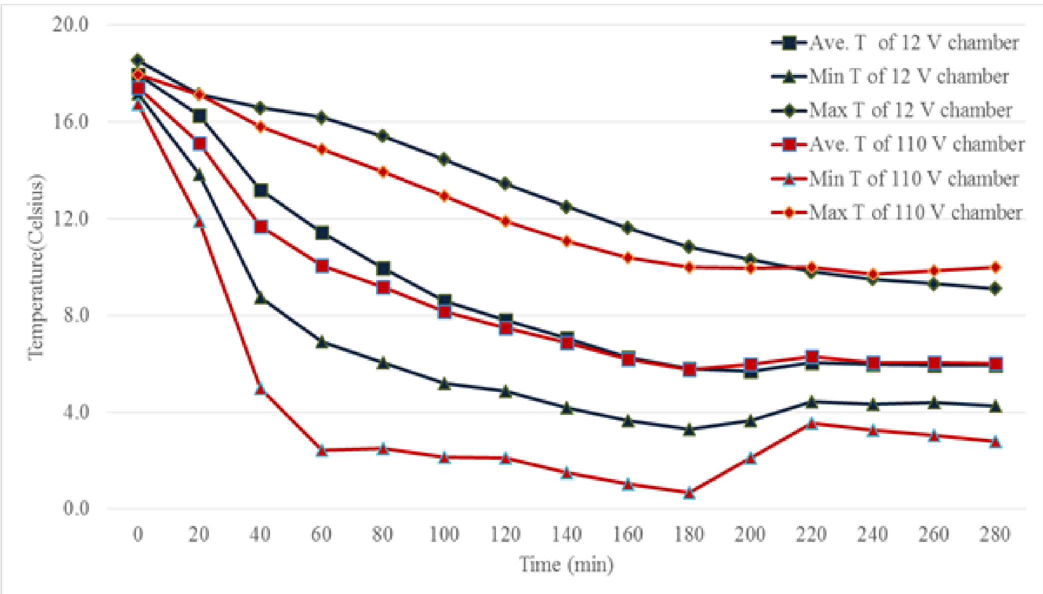

Figure 9: Summary of Cooling Speed and Temperature with Vents Open and Air Circulation Fan

Table 2 Average and Standard Deviation of Temperature in Individual Chamber

3 Hours				**4 Hours**			
110V Cooling Section		12V Cooling Section		110V Cooling Section		12V Cooling Section	
Chamber 1		Chamber 4		Chamber 1		Chamber 4	
Avg. T.	Std. D.	Avg. T.	Std. D.	Avg. T.	Std. D.	Avg. T.	Std. D.
2.06	1.94	3.72	0.56	3.72	0.61	4.67	0.44
Chamber 2		Chamber 5		Chamber 2		Chamber 5	
Avg. T.	Std. D.	Avg. T.	Std. D.	Avg. T.	Std. D.	Avg. T.	Std. D.
6.94	0.89	5.28	0.44	6.67	0.78	5.67	0.33
Chamber 3		Chamber 6		Chamber 3		Chamber 6	
Avg. T.	Std. D.	Avg. T.	Std. D.	Avg. T.	Std. D.	Avg. T.	Std. D.
8.33	1.28	8.39	2.17	7.83	1.33	7.67	1.61

Table 2 shows the average temperatures and standard deviation of temperatures in each chamber of mobile cooling system to further investigate the temperature distribution and uniformity under the operating condition (two vents open and air circulation fan on). After the cooling system was operated for 3 hours, the lowest average temperature was found in Chamber 1 while the highest temperature was occurred in Chamber 6. For the standard deviation, the Chamber 1 and Chamber 6 has relatively higher value of standard deviation. Similar temperature distribution and standard deviation changes were found after 4 hours cooling. The possible reason can be the placement of evaporator and circulation fan in the chamber. In this study, the evaporator of 110 volts cooing unit was installed near the Chamber 1 and air circulation fan was placed in the Chamber 6, which significantly reduce cooling temperatures and generate a large variation of temperatures in the Chamber 1 and Chamber 6. In addition, it was found that temperature has an increasing trend in 110 volts section (from Chamber 1 to Chamber 3) as well as in 12 volts section (from Chamber 4 to Chamber 6). This explained that upper part of 110 volts and 12 volts section has better cooling performance. Thus, it was suggested to put fresh harvested oysters from bottom to top that increasing the cooling time and compensate the lower cooling performance of the lower chambers (e.g., Chamber 3 and Chamber 6). Moreover, it was found that the lab-scale hybrid mobile cooling system with best air circulation condition (two vent open and air circulation fan open) are efficient and capable to cool oysters from 18°C down to 6°C within 4 hours cooling time. These results provided a potential future study on the location of the air circulation fan inside the cooling system to further increase the cooling efficiency.

4. CONCLUSIONS

In this study, the lab-scale hybrid mobile cooling system was designed, fabricated and evaluated. Cooling time, temperature changes, and standard deviation of temperatures in the 110 volts and 12 volts cooling sections were collected and calculated. Cooling performance of system was investigated under three different operating conditions (no vents and air circulation fan off, two vents open with air circulation fan off, two vents open with air circulation fan on). Result indicated that the lab-scale mobile hybrid cooling system is able to cool oysters down to about 10°C within 7 hours. Among the different circulation strategies, two vents open with air circulation fan on in cooling system improved cooling performance and cooled oysters from 18°C down to 6°C within 4 hours cooling time. Temperature distribution in the cooling chamber indicated that cooling system has a better performance on the upper parts (temperature around 4°C) than lower parts (temperature around 8°C) of the cooling system. These results suggested to put fresh oysters from the bottom parts to upper parts that lower parts may have longer cooling time than the upper parts. Results and findings from this study will assist to develop mobile cooling system and maintain fresh quality of oyster during the oyster farming process (e.g., harvesting, transporting). Moreover, hybrid cooling system will also help to utilize solar energy as energy resources for the 12 volts cooling unit and save additional energy consumption on the boats.

5. ACKNOWLEDGEMENTS

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