Design, development and testing of an aquaculture research temperature control system

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Abstract: A feedback based variable temperature-control system was developed for facilitating indoor aquaculture research. The system included sixteen independent tanks controlled by a personal computer using T-type thermocouples, a 32-channel multiplexer, two 8-channel analog to digital converter boards, and a set of 32 relays. Electric immersion heaters were used to increase water temperature, while a chiller and heat exchanger was used for cooling. Five-centimeter PVC airlifts allowed for aeration and circulation of water. The system was initially used to simulate fixed and diurnal temperatures but can be programmed to hold or varying temperatures from 5°C to 34°C in each tank independently. In one set of experiments, tanks were held at 10°C, 15°C and 20°C. Initial results indicated that the system was capable of maintaining and controlling water temperatures within ± 0.4°C. In a different set of experiments, diurnal temperatures (10°C ± 5°C, 15°C ± 5°C, 15°C ± 10°C, 20°C ± 5°C) were simulated. Results indicated that the control system was effective in heating the water to the desired temperatures but requires an additional chiller to cool the water. Use of variable temperature control, coupled with the independence of each tank, allows aquacultural researchers to simultaneously simulate a variety of seasonal temperatures inside their laboratories.

Keywords: recirculating aquaculture, variable temperature control, independent tanks, diurnal fluctuations, built-in biological filtration

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1 Introduction

After water and oxygen, temperature is perhaps the most important parameter influencing fish and other aquatic animals (Cotton et al., 2003; Widmer et al. 2006; Pawiworedjo et al., 2008; Saidu et al., 2018; and DelRio et al., 2019). Water temperature plays an important role in feeding, growth, reproduction, and disease outbreak (Deering et al., 1995; Yeh and Rouse, 1995; Beitinger et al., 2000; Tidwell et al., 2003; Seals et al., 1997; Rybovich et al., 2016; MacMillan et al., 1994). Temperature also influences the water quality of the fish habitat. Higher temperature reduces the solubility of oxygen, increases un-ionized ammonia (NH_3) content in water, thereby inducing stress in fish (Timmons et al., 2018). In nature, water temperature also influences the availability of feed to fish. For example, temperature affects the production of phytoplankton and zooplankton, which are consumed by

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fish and other higher order aquatic animals (Elliot et al., 2006; Heinle, 1969).

Awareness of the role of temperature in various aquatic biological processes has been of interest for decades (Heinle, 1969; Buchanan, 1998; Beitinger et al., 2000; Vidal et al., 2001 Lamoureux et al., 2006a, 2006b; and DelRio et al., 2019). Control of water temperature has been possible under research conditions in the laboratory (Hall and Saidu, 2005; Widmer et al., 2006) for some time, as have specialized systems for nominal pond temperature control in aquaculture, where geothermal energy is available (Hall et al., 2002). However, there are limits to temperature control, both from a physical point of view (Lamoureux et al, 2006a, 2006b), and more importantly from an economic point of view, as the cost of both the specialized equipment and the energy to heat or cool water can be prohibitive at a commercial scale.

Nevertheless, both in conservation applications (DelRio et al., 2019; Beitinger et al., 2000) in aquacultural applications (Saidu et al., 2012; Pawiworedjo et al., 2008) and in unique mixed cases such as open water oyster culture (Rybovich et al., 2016) there continues to be interest in understanding and controlling temperature where possible to optimize aquatic outcomes (Hall and Saidu, 2005). In recirculating systems (Greensword, 2015; Timmons et al., 2018), control of variables such as dissolved gases; solids and temperature are critical to successful outcomes.

A number of researchers have done modeling of the limits and costs of temperature control (Plaia, 1987; Lamoureux et al., 2006a, 2006b; Fakhrurroja and Setiawan, 2015), recognizing that, although often a cost, at least attempting to control temperature and other variables (Campbell and Hall, 2018) is critical to success and worthy of consideration. MacMillan (2019) attempted to clarify how to decide whether temperature was a critical or contributing variable in biological outcomes, indicating interest is still significant.

Because of the significant influence of the temperature on aquatic biology, aquaculture research, especially in natural water bodies, is challenging. Typically, researchers have a narrow time window (usually 2-3 months) to collect and study aquatic animals. For instance, if studies on fish reproduction are planned coastal waterways, the researchers will have to wait for a specific season of the year when the water temperature is conducive for the fish reproduction studies. Additionally, in natural water bodies, other factors such as predation, food availability, and water quality may affect the outcome of the research. Therefore, having access to an indoor system capable of simulating diurnal site-specific temperatures would immensely help aquacultural researchers across the world. Although commercial systems capable of temperature regulation are available for sale, they are usually expensive and not easily expandable by the end user, typically an aquacultural scientist or graduate student. Hence, the purpose of this research is to present a simple and user-friendly indoor temperature-controlled system that can allow researchers across the world to hold and study aquatic animals anytime of the year. The objectives were to (1) design and build an aquaculture tank system capable of automatic temperature regulation, and (2) test the control system to simulate constant and diurnal temperatures.

It may be noted that the system was built to hold eastern oyster, *Crassostrea virginica*, under different temperature conditions to simulate various seasons in a year. However, considering the simplicity of assembly and the use of inexpensive electronic components, the authors hope that aquacultural researchers can replicate and modify this design fairly easily and use in their respective research projects pertaining to different aquatic species.

2 Experimental methods

2.1 Design and construction of the system

Sixteen cylindro-conical food-grade tanks each of 250 L (Aquatic Eco-Systems, Inc. Apopka, FL) were used. All tanks were insulated with encapsulated fiberglass insulation (~10 cm) (Johns Manville, Denver, CO) to prevent heat loss. The tanks were filled with 200 L artificial saltwater (20 ppt) (Kent Marine, Franklin, MI). All tanks were independent from each other as shown in Figure 1. Each tank contained the following components:

(1) 5-cm diameter PVC airlift for aeration and water circulation,

(2) 300-Watt glass immersion heater (Model #300, Commodity Axis, San Gabriel, CA) for heating, and

(3) Submersible water pump (Model #306, Commodity Axis, San Gabriel, CA) for cooling. The submersible pump circulated saline water in the tank through stainless steel heat exchanger @ 2 LPM. The heat exchangers were immersed in fresh water at 4°C in a chill tank of dimensions 2.1 x 0.55 x 0.5 m (Frigid Units, Toledo, OH).

(4) The heat exchangers-constructed by affixing food grade stainless steel serving trays with covers for transferring heat between water and the chillers.

Eight tanks were connected to one rectangular chill tank (0.57 m^3) (Figure 2) Water in each chill tank was cooled by a pair of electrically operated chillers (120 V AC; 2000 W). The heat exchangers remained submerged in the chilled water (fresh water) and submersible pump recirculated water in the oyster tank (saline water, 20 ppt) through the heat exchanger. Make up water was added weekly to each tank to maintain 200-L volume through the study.

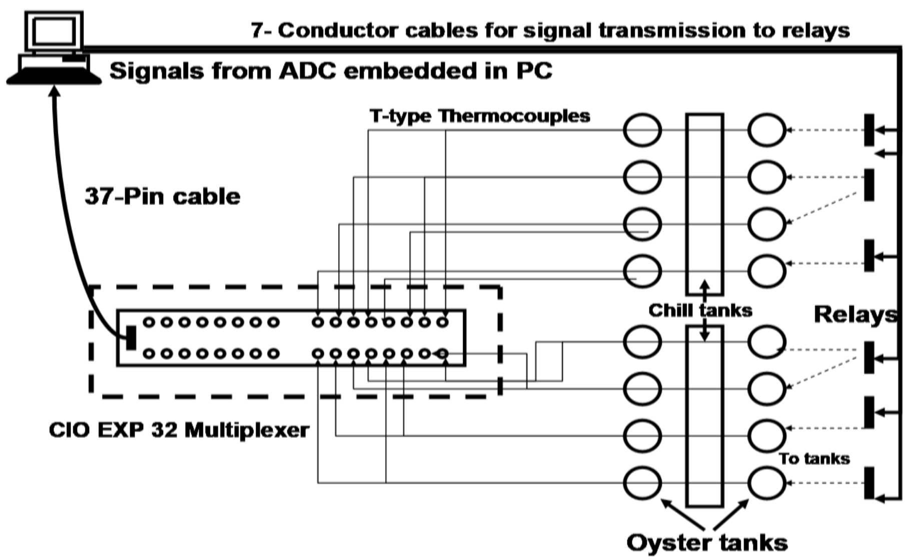

Figure 1 General schematic of the system developed at the LSUARS. A personal computer processed the signals from type-T thermocouples and relayed the output signals to the solid-state relays that actuated the pumps and heaters

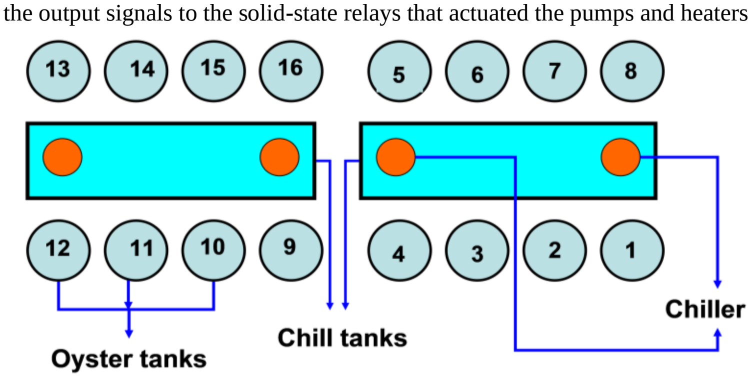

Figure 2 Schematic of chill tanks with chillers. The chillers are connected to 120 V AC to cool the water to 5°C

2.2 Hardware design and customization

The control hardware of the system included a 32-channel CIO EXP-32 multiplexer board, two 8-channel PCIM-DAS 1602/16 analog-to-digital converter boards

(ADCs) (Measurement Computing Inc., Middleboro, MA.), T-type thermocouples (Omega Engineering Inc., Stamford, CT) and a set of 15 A 4-28 VDC solid-state relays (P/N 611489, Eastman Kodak Co).

Control hardware connections and sequence of operations are shown in Figure 3. The hardware and software of the system were customized to process both analog and digital data. The junction ends of the thermocouples were soldered with lead-free electric solder and were made water resistant using silicone sealant. The measuring ends were connected to each of the first 16 analog input channels of a CIO-EXP 32 multiplexer board. The temperatures were read as differential voltages and the multiplexer amplified the voltage signals by a factor of 100. A personal computer processed the signals. The multiplexer was connected to the ADC via a CEXP2DAS16-10 special 37-conductor cable (Measurement Computing Inc., Middleboro, MA).

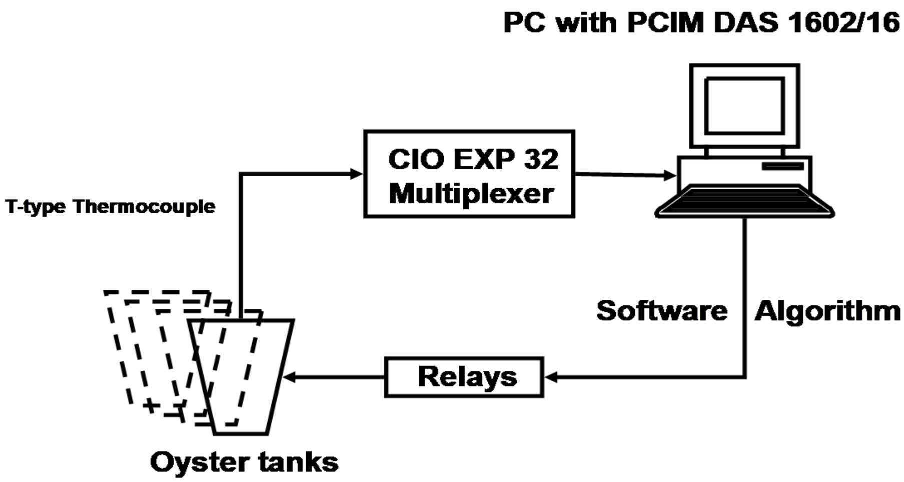

Figure 3 Type-T thermocouples from each tank were connected to a 32-channel multiplexer board

The inputs from the multiplexer were processed by the PC embedded with two 8-channel ADCs. The software allowed the ADC to send out a 5 V DC signal to the 3-32V DC solid-state relays to actuate the pumps and heaters. The signals were transmitted to the relays via a 7-conductor cable.

Based on the control software, 5 V DC signals were transmitted by the ADC through a BP 40-37 (Measurement Computing Inc.) ribbon cable that brought 40-pin on-board connections out to 37-pin male connector on computer back plate. Two C37 FF-2 (Measurement Computing Inc.) ribbon cables were used for transmitting output signals. One end of C37 FF-2 cable was connected to male pin of BP 40-37 and other ends were soldered to 8-pin standard male DIN connector (Marlin P. Jones & Associates, Inc.,).

Seven-conductor cables were used to connect C37 FF-2 cables. Both the ends of the 7-conductor cables were soldered with 8-pin standard female DIN connectors (Marlin P. Jones & Associates, Inc. Lake Park, Florida). One end of the 7-conductor cable was connected to the relays and other end was connected to each of the C37 FF-2 cable. The output signals (5V DC) closed the 110V AC circuitry and actuated pumps and heaters in the tanks as dictated by software.

2.3 Software design and logic

The software for the control system was developed in Visual C++ (Microsoft Corp, WA) executed on a Windows platform. The control was executed every 3 min. The program measured the temperature every 3 sec and a 3-minute average for each tank was computed. The computed average was compared with the required temperature. For every execution cycle, one of the following conditions was satisfied.

(1) If the actual temperature (T_a) was above the required temperature (T_r), the pump was switched on to cool the water.

(2) If the actual temperature was below the required temperature, the heater was switched on to heat the water.

(3) If the actual temperature was equal to required temperature, heater and pump were switched off.

Depending on the actual temperature of water in each tank, the water was either cooled or heated, until desired temperatures were reached (Figure 4). The system was programmed to hold constant temperatures or follow sinusoidal temperature variations and could be programmed to follow complex time-temperature histories if needed.

2.4 Testing of the system

The system was tested continuously for ten months. The primary focus was to evaluate its ability to hold constant temperatures and to simulate diurnal temperatures. For the constant temperature regime, three temperatures, 10°C (four replicates), 15°C (six replicates), and 20°C (four replicates) were selected. Similarly, for the diurnal temperature regime, the average temperatures were set at 10°C, 15°C, and 20°C. A diurnal fluctuation of ± 5°C was imposed on each average temperature (two replications each). Additionally, to evaluate the physical limits of the system an additional fluctuation of ± 10°C was imposed over 15°C.

To mimic an actual aquacultural tank system, prior to the testing, each tank was loaded with 60 eastern oysters, C. *Virginica* that were collected from Grand Isle, LA. The oysters were placed on circular trays (60-cm diameter) fabricated from plastic coated hardware cloth reinforced with 1.25 cm PVC tubes.

The oysters were fed algal paste (1800 Instant algae®, manufactured by Reed Mariculture, Campbell, CA) twice daily as per the manufacturer's recommendation.

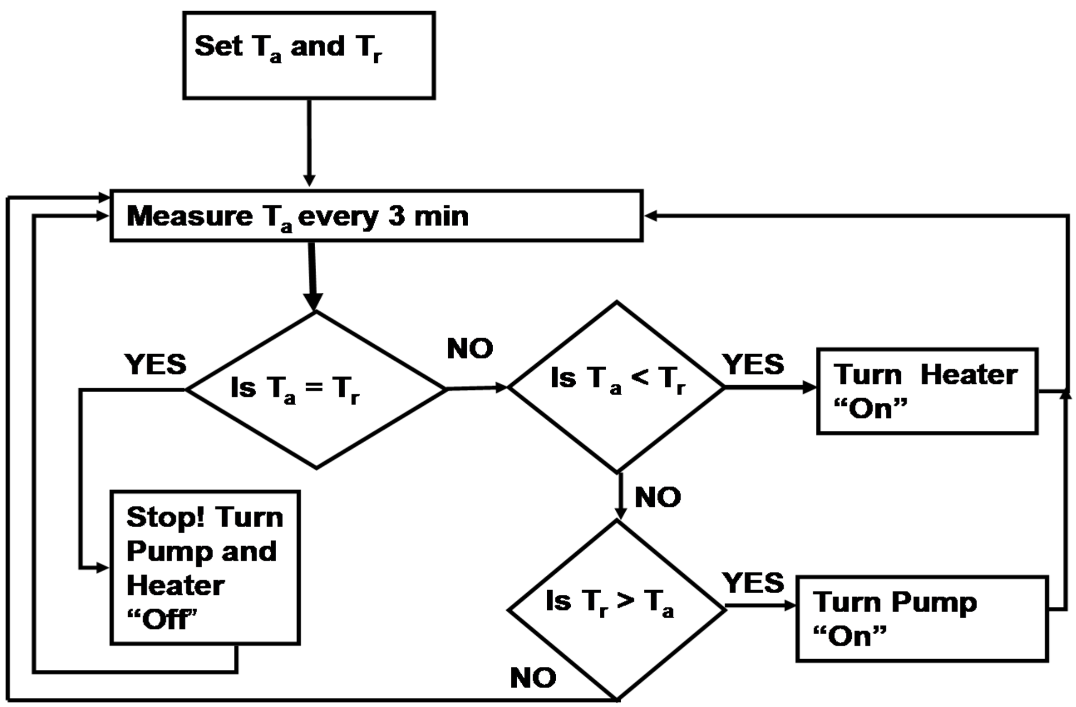

Figure 4 Programming logic for the software consisted of three scenarios

The water was either cooled or heated. If the measured temperature was same as the required temperature, pumps and heaters were inactivated.

3 Results and discussion

The system monitored the water temperatures every three minutes and hence each day consisted of 480 temperature readings. Hence, for simplicity, the daily average temperature was computed for each tank and the same were used in data analyses. For tanks in which diurnal temperatures were imposed, we used the data obtained directly from the software (averaged over 3 min).

The system was able to maintain the temperatures within ± 0.5°C. Around day 20, the power bars associated with tanks 5 and 14 were tripped off due to electrical overloading, allowing ambient temperature to raise water temperature approximately 1°C.

The daily average water temperatures in the tanks are shown in Figures 5, 6, and 7. Figure 5 shows the temperatures in tanks 5, 14, 15, and 16. For most of the study period, the system was able to maintain water temperatures around 10°C in all four tanks. However, around day 20 the tanks 5 and 14 experienced a steep increase in water temperature. A careful investigation of the system revealed that power strip supporting tanks 5 and 14 was tripped due to electrical overloading. The problem was rectified by drawing power from two separate sources and subsequently tanks 5 and 14 were able to maintain the programmed temperatures.

Figures 6 (6 tanks) and 7 (4 tanks) show the water temperature in tanks where water temperatures were programmed to maintain at 15°C and 20°C respectively. For both temperature regimes, 15°C and 20°C, the water temperature in the tanks was with ± 0.2°C from the required temperatures. Considering the standard range of error of 0.5°C-1.0°C for type-T thermocouples (omega.com), the data suggested that all replicates at a given temperature regime were same.

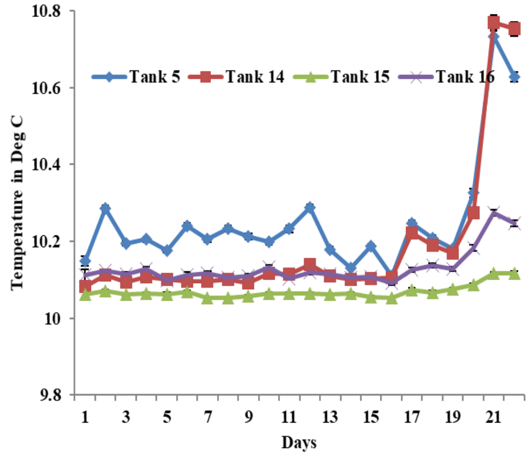

Figure 5 Four tanks (n=4) were programmed to maintain constant temperatures of 10°C

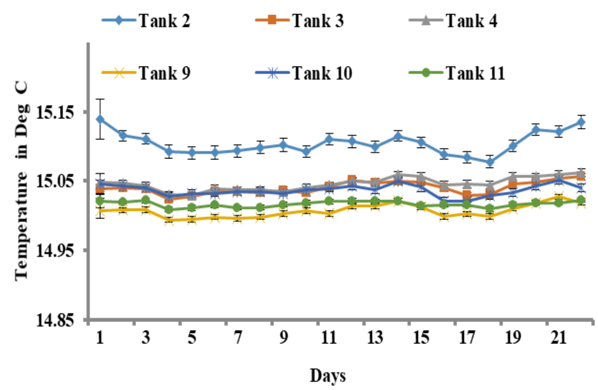

Figure 6 Six tanks were programmed to maintain constant temperatures of 15°C

The tanks were able to maintain the temperatures within ± 0.2°C, with variability of individual tanks closer to ± 0.1°C.

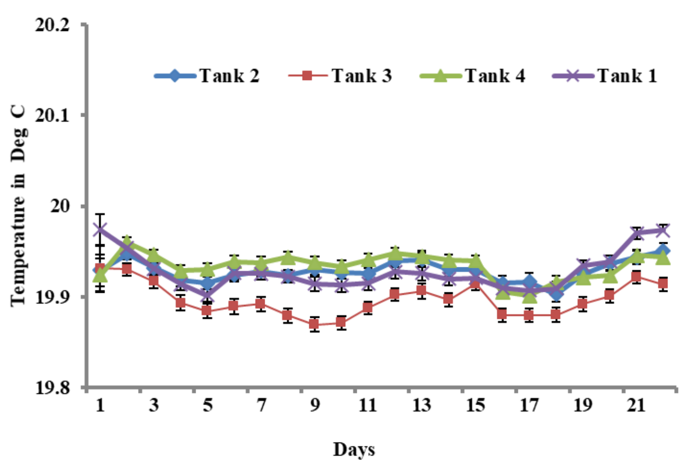

Figure 7 Tanks (n=4) were programmed to maintain constant temperatures of 20°C

The tanks were able to maintain the temperatures within ± 0.2°C.

Additionally, a detailed analysis of the temperature dynamics for a typical 24-hour period was carried out using Microsoft Excel. Figure 8 shows a typical 24-hour temperature data in the tank that was maintained at 15°C. The mean of differences between the required and actual water temperatures was **-0.1°C** with a standard deviation **0.03°C**, which means that on an average the actual temperatures are **higher** than required temperatures. The system requires **cooling** to maintain the required temperatures. Differences between required and actual temperatures for each regime for a typical 24-hr period are shown in Table 1.

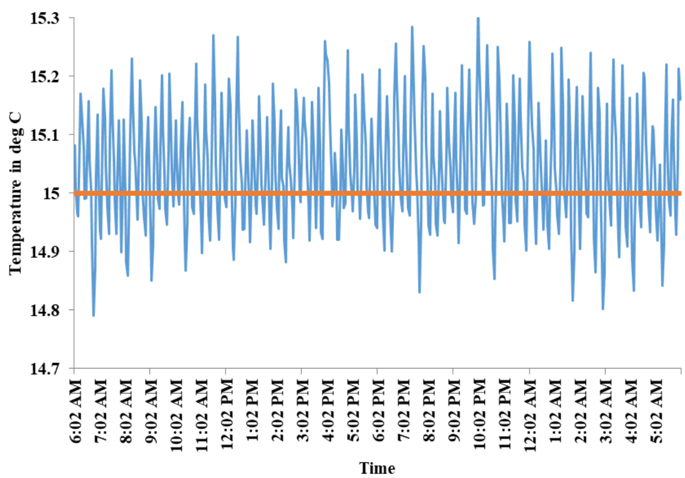

Figure 8 A constant temperature of 15°C was simulated in a tank for a 24-hr period to study temperature dynamics.

For the given 24-hr period, the average actual temperature was above the required temperature indicating a net cooling requirement of the system.

After evaluating the system's ability to maintain constant temperature in the tanks we continued testing the system to maintain diurnal temperatures. Figures 9, 10, 11, and 12 show the temperatures in the tanks that were programmed to maintain 10°C±5°C, 15°C±5°C, 20°C±5°C, and 15°C±10°C respectively.

Based on the temperature data obtained from the software, it was found that the control system was efficient in holding and simulating diurnal water temperatures for regime, 20°C±5°C, but not as effective for the regimes, 10°C±5°C and 15°C± 10°C. In all the temperature regimes it was observed that the system was effective in heating the water to the desired temperature. However, the system had difficulties in cooling the water down to below 7°C. As evident from the Figures 9 and 12, the water did not reach 5°C at midnight as programmed. This is probably because water in all tanks was constantly in circulation, the load on the chiller increased. Despite the chillers' peak performance, it reached a point beyond which further cooling was not possible. Also, the holding capacity of chill tank was around 500 L. However, total water that was to be cooled was around 1600 L. An additional chiller in each chill tank could facilitate faster cooling of water in the tanks to the desired temperature. Another option would be to heat a few chosen tanks while chilling others to avoid simultaneous heating or cooling in all tanks. This will not only reduce load on chillers but also minimize concomitant overloads. Also, feed forward control could be used to reduce peak heating and chilling rates for a given hardware configuration. Clearly, the system was quite functional, but these additional changes could improve overall system performance and possibly reduce energy costs.

Table 1 Means and variance of the temperature differences between required and actual temperatures for a 24-h period.

Description of the regime	Temperature (˚C)	Mean of the Difference (˚C)	Variance of the Difference (˚C)	Remarks (Required Energy)
Constant	10	-0.19	0.02	Cooling
Constant	15	-0.10	0.03	Cooling
Constant	20	0.068	0.01	Heating

Diurnal	20 ± 5	0.02	0.04	Heating
Diurnal	15 ± 5	-0.42	0.53	Cooling
Diurnal	15 ± 10	-1.63	5.69	Cooling

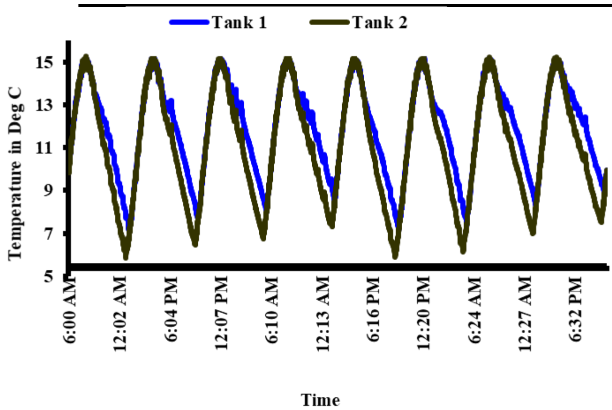

Figure 9 A variation of ± 5°C was imposed over an average temperature of 10 °C

The system had difficulty in cooling the water to 5°C at midnight, as ambient temperatures ranged from 25°C-30°C.

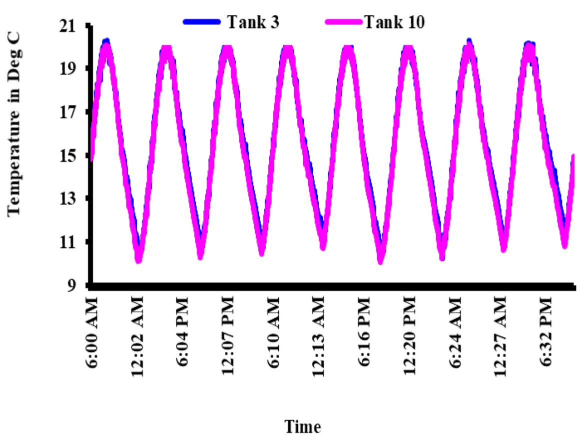

Figure 10 A variation of ±5°C was imposed over an average temperature of 15°C

The system was able to maintain the required temperatures within ±0.5°C.

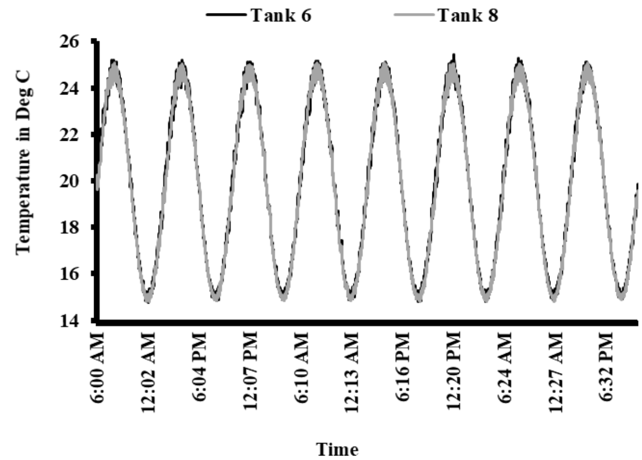

Figure 11 Diurnal temperatures were simulated in the tanks for an 8-day period.

The average temperatures were set at 20°C. Daily variations of ± 5°C were imposed such that temperatures typically peaked around noon and lowest temperatures occurred around midnight.

One of the salient features of this control system is its scalability and system independence. With the present configuration, the system could be scaled up to 64 independent tanks. Because all tanks were independent, different tanks could be maintained at different temperatures and different salinities. Additionally, there would be no mixing of water between the tanks which could eliminate pathogen transfer. The control system is expected to provide real-time control over the water temperature and the flexibility necessary for facilitating aquaculture research in the laboratory. Because the system could be used for a temperature range of 7°C-34˚C, experiments could be planned year-round. The feedback received from the system may be utilized to modify the system dynamics. For example, the program execution time (presently set to 3 min intervals) may be decreased to 1 min interval to reduce sudden cooling or heating. Moreover, the control system also allows for programming variability with which different seasonal temperatures could be simulated in different tanks. For example, the system could be used to simultaneously simulate spring, summer**,** and winter temperatures in tanks. As each tank had built-in features for heating and cooling, and could be programmed to different temperature regimes, the control system could be useful to study multiple species that have different temperature and salinity requirements.

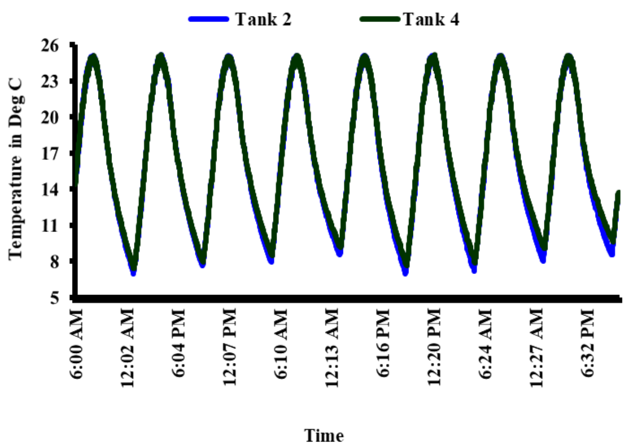

Figure 12 Diurnal simulations 15°C±10°C were simulated for an 8-day period to test the physical limits of the system.

Though the tanks reached highest temperatures during noon, they had difficulty in reaching the coolest point (5°C) at midnight due to chiller limitations. Later designs added improved heat exchanger, larger chiller and insulation on tanks to address these issues.

4 Conclusions

(1) A feedback-based temperature control system consisting of 16 independent tanks was developed to expand the capabilities of indoor aquacultural research.

(2) The design of the system allowed for independent and variable control of temperature in each tank. The system was able to hold and simulate diurnal temperatures between 10°C and 25°C.

(3) Limitations in the ability to hold temperatures more than 10°C±0.2°C from ambient were due to small chiller size and limited insulation, added after the end of these experiments.

(4) The system could also be used for more complex control of temperature or other parameters for controlled duplicates of in-field systems or to investigate the influence of other water quality parameters on aquatic life.

(5) The system had high value to cost, and could be replicated by others using similar technologies, based on the design presented here.

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