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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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Title of Dissertation (ゼロエネルギー低温貯蔵庫の開発)

学位論文要約：
Dissertation Summary

Recent world energy consumption pattern showed that the inadequacy of fossil fuel and the increase demand of energy for industrial sector are the future energy security concerning issue around the world. In developing countries, most agricultural areas do not have a grid electricity supply or electric-powered refrigeration systems to maintain the storage temperature constant at low level for fruit and vegetables. Even most farmers do not have the financial capability to purchase, maintain, and operate expensive cooling systems. This lack of refrigeration system causes decaying of the large quantities of fruit or vegetables. As a result, sharp differences in food supplies between the harvest and off harvest periods was observed in the affected areas. Therefore, prices of agricultural products are highest during the off-season and cheapest during the harvest season. In this contest the passive evaporative zero energy storage without using electricity is a low cost, rural area oriented on-farm simple storage system, and found very effective for increasing the shelf life of stored fruit and vegetables.

In this study, a zero energy cool storage system with no electric energy was developed. **Figure 1** shows the zero energy cool storage system which consists of a storage chamber (A) and two types of cooling systems, evaporative cooling system (B) and solar-driven adsorption cooling system (C). The storage chamber has lava plates and bricks made double walls, an evaporative medium (gravel stone-sand-zeolite) between the double walls, a half below ground storage space, and a natural airing system from bottom to top through the evaporative medium. The cooling of the evaporative cooling system is achieved by the evaporative cooling of water supplied to the evaporative medium. The cooling of the solar-driven adsorption cooling system is attained by the evaporative cooling of alcohol during adsorption phase, that produced ice and the produced ice was then stored inside the ice box to reduce the storage chamber temperature until the next cooling cycle started.

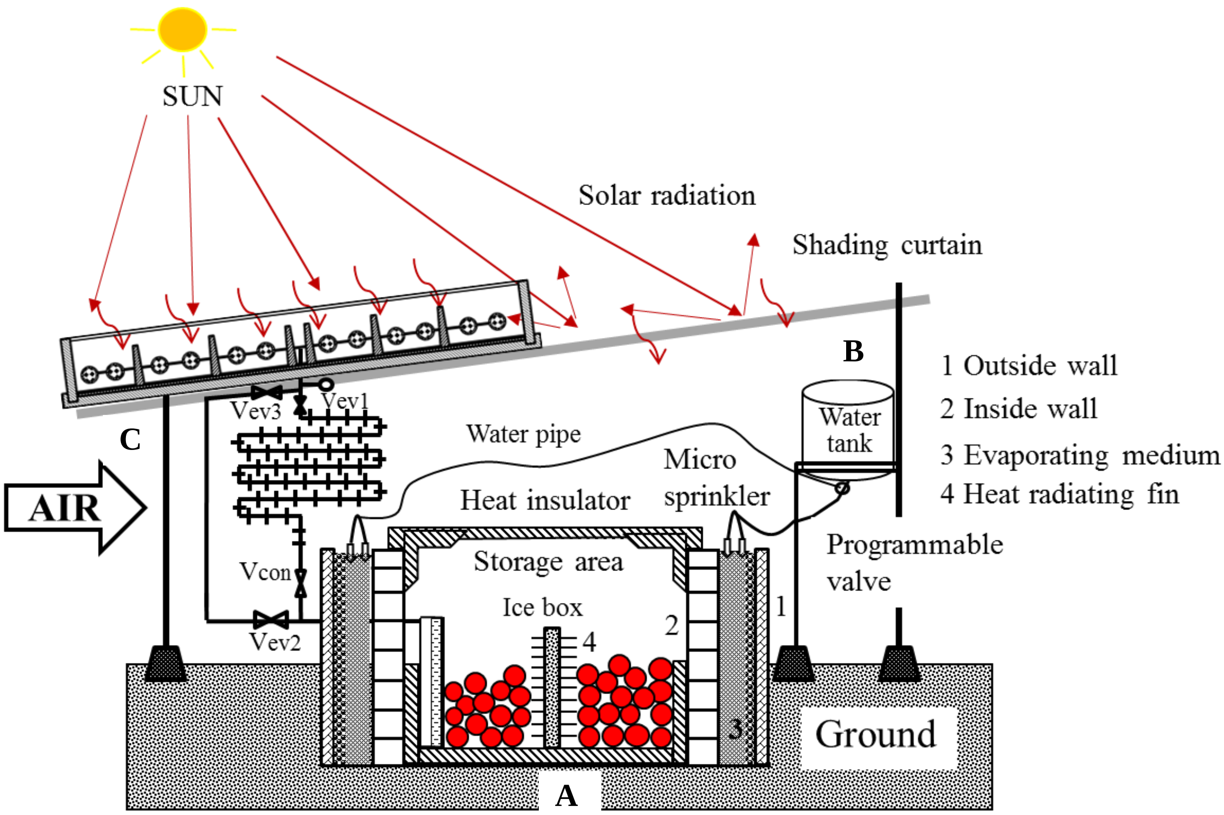

Fig.1 A new zero energy cool storage system. It consists of storage chamber **(A)**, water supply and evaporative cooling system **(B)** and solar-driven adsorption cooling system (**C**)

First, I'll show you the fundamental evaporative cooling effects. **Figure 2** shows typical diurnal changes in the solar radiation, the outside temperature, watering and the inside temperature and inside RH of the ZECC on sunny and rainy days, respectively. From the figure, it could be observed that the solar radiation first increased the outside temperature, and then the outside temperature increased the inside temperature. Cooling of the zero energy cool storage system is achieved by applying water to the evaporative medium and airing which revealed a zero energy cool storage system can decrease the inside temperature to 15°C and it's detachable clay water tank placed inside the storage area increased the relative humidity level to 80% and maintained them at the same level for a long time. New material such as PVLS plate, sand-zeolite-gravel stone, and polystyrene sheet were found to be very effective in terms of heat transfer, aeration, evaporation, and heat insulation. A solar chimney enhanced the sustainable natural air flow over the surface of the wet sand-zeolite-gravel stone based evaporative medium through absorbing more water molecules. As a result, the cooling time of stored tomato and eggplant inside a zero energy cool storage system is shorter and fresh tomato and eggplant stored inside the zero energy cool storage system indicated signs of spoilage after about 19 and 9 days, respectively, compared with 7 and 4 days, respectively, for fruit stored outside.

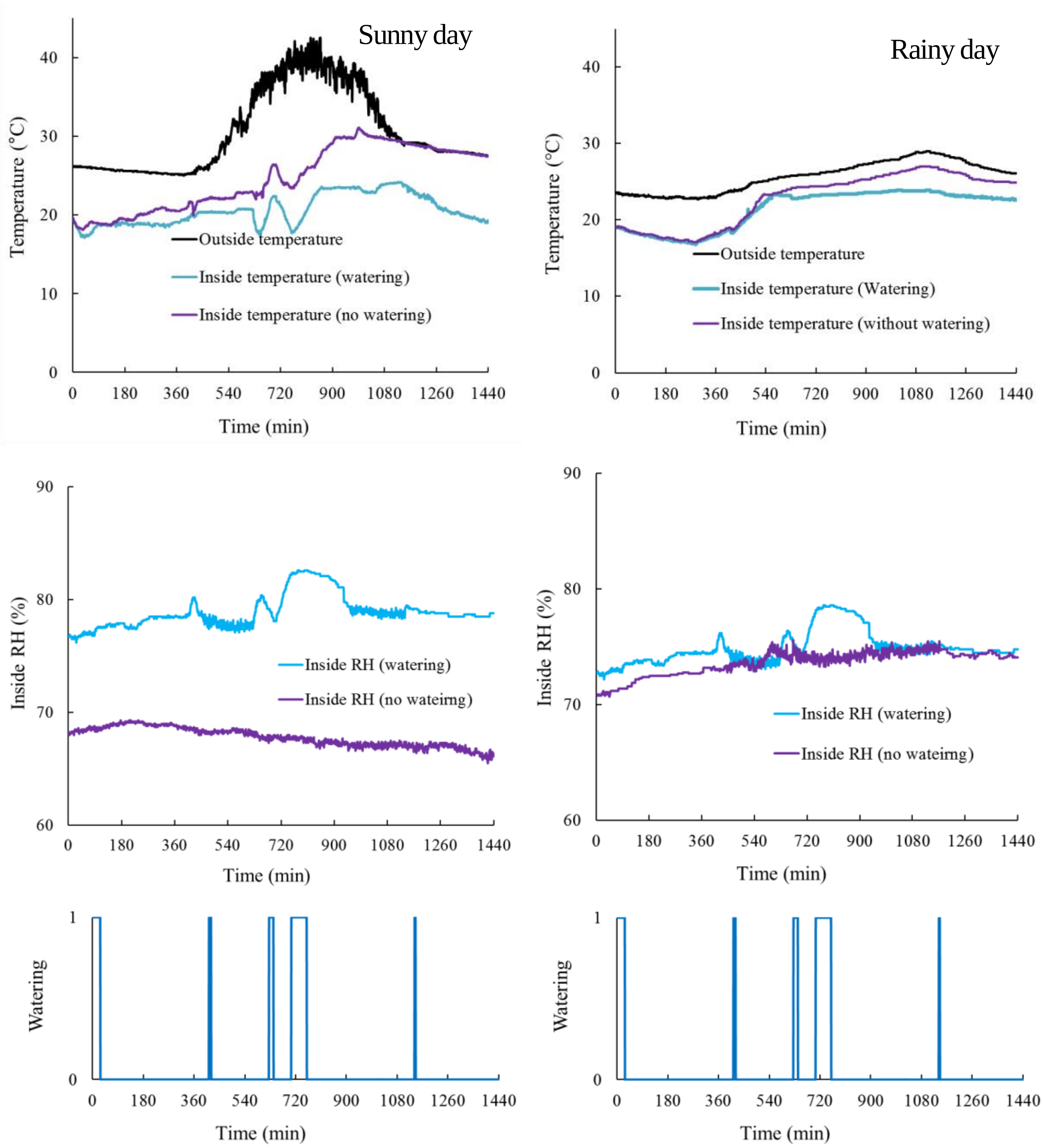

Fig. 2 Diurnal changes in solar radiation, outside temperature and inside temperature and RH in the zero energy cool storage system under shading and watering conditions

Next, since the inside temperature of the zero energy cool storage system is affected by climate factors such as outside temperature, watering and inside RH and the input-output system is characterized by complexity and uncertainty, an intelligent optimization technique combined with neural networks and genetic algorithms was applied to minimize the inside temperature of the zero energy cool storage system. The control input was watering which is supplied to the filler made from sand and zeolite between the brick walls. First, a three-layered neural network with a time-delay operator was used for identifying this dynamic system. Then, the genetic algorithm was used for searching for the optimal 8-step ON-OFF intervals of watering which minimize the inside temperature of the zero energy cool storage system through simulation of the identified neural-network model. High diversity of the population by adding some individuals from another population and having high crossover and mutation rates shortened the searching time for the global optimal value. **Figure 3** shows an optimal control performance. The optimal intervals obtained for the watering schedule were T_1= 35 min ON, T_2= 55 min OFF, T_3= 35 min ON, T_4= 55 min OFF, T_5= 35 min ON, T_6= 55 min OFF, T_7= 35 min ON, T_8= 55 min OFF, T_9= 35 min ON, T_{10}= 55 min OFF, T_{11}= 35 min ON, T_{12}= 55 min OFF, T_{13}= 35 min ON, T_{14}= 55 min OFF, T_{15}= 35 min ON, and T_{16}= 55 min OFF. The average inside temperature for this optimal control was 4.0°C lower than that for the continuous watering for 24 hours, and was also 7.5°C lower than that for no watering. Furthermore, the shelf-life of the tomatoes during storage in the optimized zero energy cool storage system was extended from 7 to 16 days. Thus, it is concluded that the zero energy cool storage system storage system optimized with an intelligent optimization technique combining with the neural network and genetic algorithm achieves a minimum inside temperature and is therefore effective for storing fruit and vegetables from the viewpoints of low cost and energy saving.

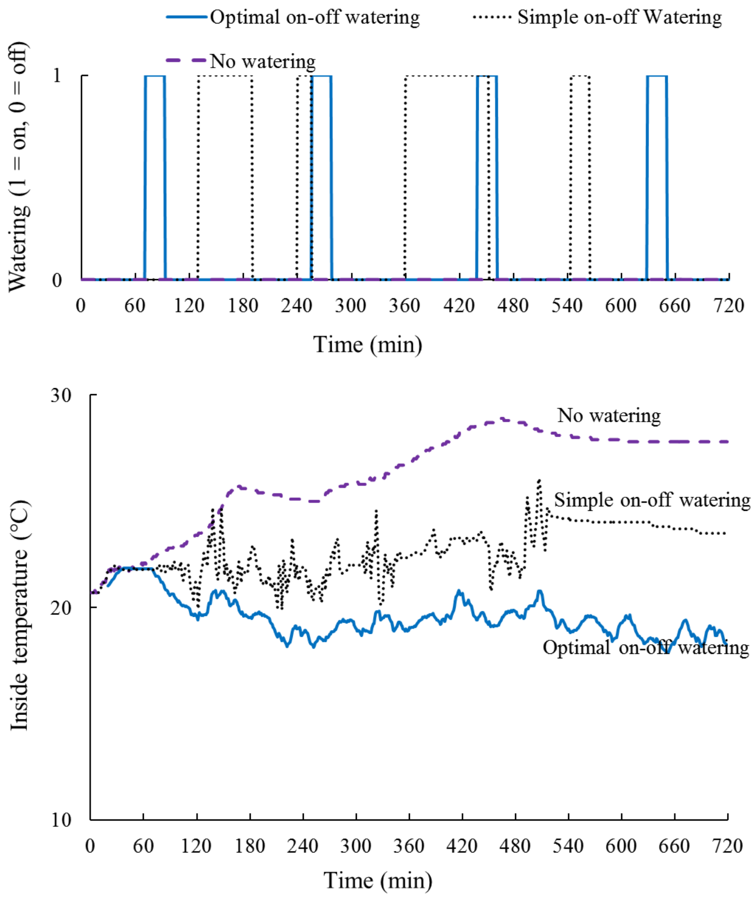

Fig. 3 The optimal control performance of the inside temperature of the zero energy cool storage system by the control of the optimal watering based on optimal ON-OFF watering intervals

Finally, a solar-driven adsorption cooling system was applied to this cooling system. The thermodynamic cycle of a solar-driven adsorption refrigerator is illustrated in a Clapeyron diagram (ln P vs. 1/T diagram), as shown in **Fig. 4**. At the beginning of the cycle, the isosteric heating cycle (during the day), the activated carbon and methanol-filled copper absorber tube inside the solar collector was heated by solar radiation and continued until the activated carbon rose to temperature T_{gen}. As a result, the vapor pressure of the desorbed methanol increased to P_{con}. During this process, both the condenser and evaporator were isolated from the absorber tube of the solar collector by valves V_1, V_2, V_3, and V_4. Once the methanol vapor pressure reached P_{con}, valve V_2 was opened and valves V_1, V_3, and V_4 were closed to equalize the absorber tube inside pressure with the condenser pressure and to allow the methanol vapor to flow towards the condenser. This process is called isobaric heating (desorption). The temperature continued to increase, but the amount of methanol inside the activated carbon continued to decrease as more adsorbate methanol vaporized from the activated carbon. During isosteric cooling, the condensed methanol was stored inside the evaporator by opening valve V_3, while valves V_1, V_2, and V_4 were closed. During the night, solar radiation decreased to 0 and the temperature of the absorber tube of the solar collector fell because of convective and radiative heat transfer to the surrounding environment. This process is called adsorption and during this process, both temperature and pressure inside the absorber tube dropped until the pressure reached the evaporator pressure. During this stage, valve V_4 was opened and valves V_1, V_2, and V_3 were closed to allow the condensed methanol, vaporized by absorbing heat from the water tank, to flow towards the activated carbon of the solar collector absorber tube. As a result, the temperature of the water in the water tank decreased to such a level that liquid water changed to solid ice. Later, during the day when the melted ice circulated through the copper heat-exchanging tube inside the cold storage, the warm air inside it came into contact with the heat exchanger tube. As a result, the temperature inside the storage chamber decreased until the next ice producing cycle started.

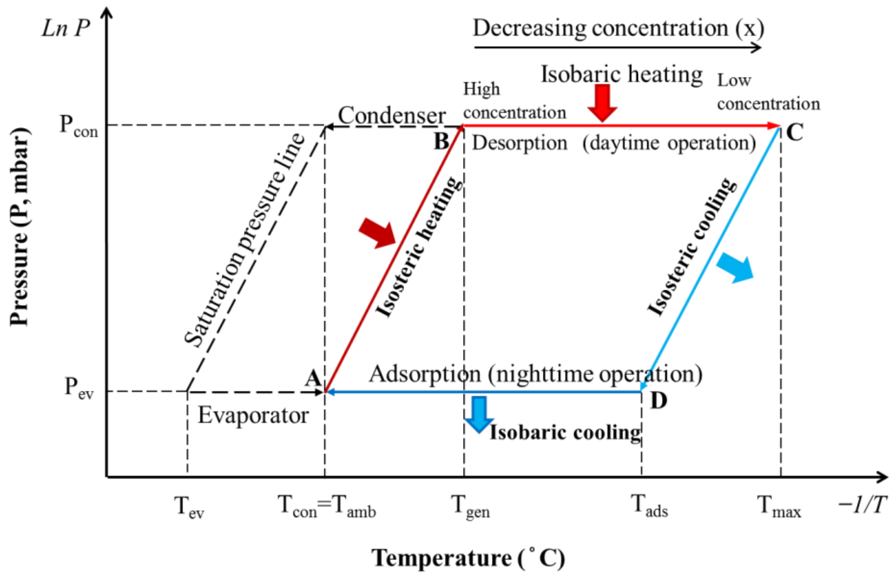

Fig. 4 Clapeyron diagram for the basic solar-driven adsorption refrigerator thermodynamic cycle

Figure 5 shows the cooling performance of the new zero energy cool storage system. The solar-driven adsorption refrigerator produced about 3.5 kg of ice per day with a solar COP of 0.071. The ice was then stored in the ice box and cooled the storage space well throughout the following day. The inside temperature during the diurnal change was lowered to 20.9°C by watering and then further reduced to 10.1°C by applying the solar-driven adsorption refrigerator, while the ambient outside temperature was 32.0°C. The average inside temperature of the new zero energy cool storage system for twenty three days was 12.07°C, while the average outside temperature was 31.5°C, and the shelf life of tomatoes was extended from 7 to 23 days. Physiological loss in weight (PLW) of 5.4%, firmness of 0.3 kg·cm^{-2}, TSS of 5.1% and pH of 4.7 were obtained after storing tomatoes for 23 days. Thus, the new zero energy cool storage system proposed here is very effective in lowering the storage temperature and expanding the shelf life of fruit and vegetables in an area without electricity. This system can help to store medicine and vaccine in the remote areas of the developing countries. The effectiveness of this new system could be improved by finding new light weight, low cost, high heat conducting, and environmental friendly materials for collector, condenser and evaporator; it is necessary to conduct field trial in the farmer’s level.

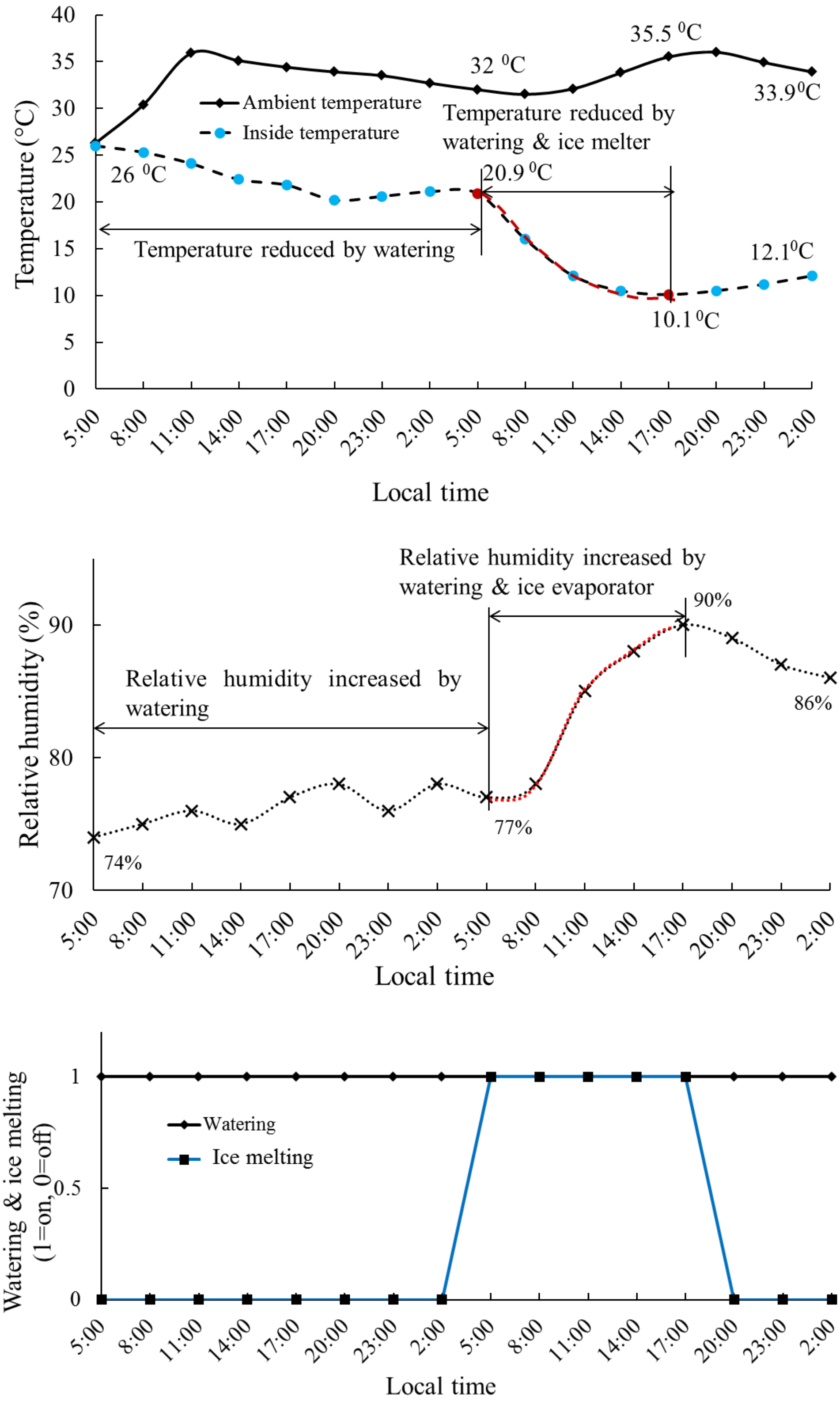

Fig. 5 Short-term changes in inside temperature of the new zero energy cool storage system

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Thus, the new zero energy cool storage system has potential to be an alternative to conventional electric powered expensive cooling storage for fruit and vegetables in the rural areas of the developing world. Future success on the dissemination of brick wall cooler storage system towards farmer’s community may imply on more study on newer type of low cost heat exchanger material; further study on its economic, environment and social impacts; low cost postharvest treatment and packaging for brick wall cooler storage system; extensive farmers awareness and other dissemination measures; and public awareness and other dissemination measures.