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Research Article

Radiant Floor and Traditional Cooling System Applications in Agricultural Product Storages

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Abstract:
The fluctuated temperatures and relative humidity inside storages are not suitable for food and agricultural products since these parameters directly affect product moisture contents, freshness, and integrity. With a limited amount of research, in this work, traditional vapor compression (fixed- and variable-speed compressors) and radiant floor cooling systems were experimentally investigated as solo and combined systems in no heat load and heat-loaded cooling-storage rooms. The latter systems were newly introduced in storage applications. When the compression systems were examined, they were set at 18°C and 22°C to find their operating effects. The results showed that the radiant floor cooling systems not only assisted both compression systems to consume less energy, but the floor cooling systems also created fewer fluctuating conditions. The combined systems were highly recommended to be used in storages containing products that were sensitive to fluctuating conditions such as ready-to-eat and fresh fruit products. The energy consumption investigation imparted valuable information for operation costs.

Keywords: *Cooling storage, Refrigerating systems, Radiant floor cooling system, Vapor compression system, Heat transfer*

1. Introduction

Refrigeration systems are the most important systems in food preservation and agricultural product storage because they provide air conditions such as temperatures and relative humidity according to suitable conditions for agricultural products. Electrical power is one of the main powers consumed by the systems. Among activities that consumed energy in the meat industry, cooling systems consumed the most energy [1]. The systems play an important role in greenhouse gas emissions since they consume energy, which is mostly produced by fossil-fuel power plants. In the UK, the food industry was responsible for 22% of the emissions, and food transportation was responsible for 40% [2].

All members of the United Nations have taken action on 17 sustainable development goals, and climate change and responsible consumption and production are among the sustainable development goals. Many countries all around the world recognized and responded to climate change and the energy consumption crisis, such as the Strategic Energy Technology Plan of the European Union and the 12th five-year Plan of China [3].

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Temperatures and relative humidity play significant roles in agricultural issues such as agricultural product quality, storage periods, and delivered quality in export. Storage temperatures affect the storage periods of durians during their export; the proper temperatures inside the export container relate directly to their freshness [4]. Srisubati et al. [5] experimentally investigated the paddy yellowing rate effected by temperature, relative humidity, and water activity. Temperatures and relative humidity were key parameters in preventing problems with sugar contents, crystal structure, and caking of raw sugar in the raw sugar export delivery [6]. There was a report by Babarinsa (2006) stating that refrigerating storage could extend the shelf life of tomatoes by about 10 days. When tomatoes were stored in refrigerators for 9 days, they caused a significant increase in biofilm [7] and physiological changes [8]. The fluctuated temperatures and humidity in tomato storage often occurred in refrigerated transportation [9, 10]. These fluctuated conditions affected the postharvest decay of tomatoes. Since tomato temperature and cooling time relied on cooling systems [11], the temperature range to store tomatoes from 18°C to 22°C was investigated in the literatures [12, 13].

As a result of the rapid growth of the market for healthy fruit and ready-to-eat products, acceptable fluctuated temperatures, and relative humidity values in the storage of the dipped fresh-cut nectarine were specified by Wen et al. [14]. These parameters were also reported by Kowitcharoen et al. [15] to influence the antioxidant activity of the sugar apples at their harvest and during their storage. Low relative humidity values were indicated in the Thai herb-essential-oil coating investigation as the proper relative humidity of the air inside the storage [16].

The vapor compression system is the ubiquitous refrigeration system, which one may call the traditional convection refrigeration system. There are four main components in the vapor compression refrigeration cycle: an evaporator, a refrigerant flow control, a condenser, and a compressor. The compressor performs as the heart of the system as it circulates refrigerant throughout the cycle. Two well-known compressors that are distinguished by their controlled systems are a fixed-speed compressor (FSC) and a variable-speed compressor (VSC).

The numerical investigation was carried out by Chu et al. [17] to find the airflow organization in different conditions and the optimal air supply parameters by using heat comfort, ventilation efficiency, and energy utilization coefficient. They concluded that different air supply angles and different air supply speeds affected the thermal comfort of the work area, and the better the thermal comfort, increased the energy utilization coefficient. When the air supply temperature differences were in a range of 4°C to 8°C, the thermal comfort was better while the energy utilization coefficient did not change.

On refrigerating systems, heat exchangers can be used. Focused on expressing the air temperature, air relative humidity, and energy consumption (EC) profiles of two refrigerating storages using the HFC-32 fixed- and variable-speed compressor (FSC and VSC) systems before and after the double-pipe heat exchanger (DPHEx) installations. Both storages had heaters, humidifiers, and hot water pots to generate heat and humidity at 18 ◦C and 22 ◦C, a storage temperature range for many postharvest products. From the results, both systems performances in reducing the EC of the FSC and VSC systems were enhanced by using the DPHExs. The EC of the FSC and VSC systems were reduced by 52.33 % and 17.19 % at 18 ◦C and 50.63 % and 20.00 % at 22 ◦C, respectively. All experiments with storage using the FSC system resulted in fluctuating profiles. This research information provides basic information for preliminary decisions about using DPHExs in postharvest refrigerating systems and selecting systems targeting the FSC and VSC systems in different situations. The power demand and operating cost relating to agricultural product storage can be calculated by using the EC correlation of each cooling system. Product freshness and abundance depend on fluctuating conditions, postharvest storage conditions, temperature, and relative humidity. The VSC system, coupled with the DPHEx, demonstrated enhancements on the EC and stable conditions [18].

Another refrigeration system used in large areas is the radiant floor cooling system. This cooling system consists of water tubes embedded in the floor, a water flow control, a pump to circulate the water, and a water chiller or boiler to provide cold and hot water, respectively. There is a standard code, ISO11855, to design, install, operate, and inspect the system. This system has been used in many buildings where the existing cold water is produced by the chillers. The radiant floor cooling system can mainly absorb sensible heat from the refrigerating space. One concern in applying the floor cooling system to agricultural product storage is water condensation from vapor in the air on the cooling floor. Tube installation on the floor requires less skill than the installation on the ceiling. After the tube installation, a slab is made on the tube. Pouring a concrete slab on ground is easier than pouring on ceiling. Evaporators, lighting, and humidifying systems inside agricultural storages are equipped on the top part or ceiling of the storage. If there are chilled water tubes on the ceiling, installing other systems must be extremely careful. Chilled water ceiling can be fabricated but condensed vapor on the ceiling may affect and damage lighting and other electrical systems near the ceiling. The radiant floor and traditional cooling systems were installed in two identical-twin commercial buildings in India [19] to investigate for their energy consumption, comfort, and cost. Area, residents, arrangement, and lighting in both buildings were similar. One building was equipped with only the traditional systems while another was equipped with only the radiant floor systems. The traditional systems, having the energy index of 38.70 kWh/sqm, consumed 440,000 energy-units while the radiant floor systems, having the energy index of 25.70 kWh/sqm, consumed only 269,000 energy-units. The results implied that the radiant floor cooling systems took 33% less energy consumption than the traditional systems. Later, the coupled systems were numerically investigated by using FLUENT and EnergyPlus, to find their energy consumption [20]. The radiant floor system coupled with the Fan Coil Units (FCUs) consumed 17.50% less energy than the traditional systems or traditional Fan Coil Units, while the radiant floor system coupled with the Dedicated Outside Air System (DOAS) consumed 30.30% less energy than the traditional systems. However, there was a limited amount of research presenting the radiant floor cooling system in the agricultural storages. Energy exchange between floor and two agricultural product storage was theoretically and numerically analyzed by Sokołowski and Nawalany [21]. Mizuno et al. [22] utilized the floor cooling system to cool roots of strawberry by feeding chilled water to strawberry pots in summer. Effects of strawberry growth and products such as flowering and yields were observed and analyzed.

Since the radiant floor cooling system can be operated coupled with the vapor compression systems as the combined refrigerating systems for agricultural product storage, this work was aimed at experimentally investigating two traditional refrigeration systems, the vapor compression and radiant floor cooling systems, in two imitated storage rooms. The radiant floor cooling systems were installed in both rooms, with a room equipped with the vapor compression system using the fixed-speed compressor (FSC) and another room equipped with the system using the variable-speed compressor (VSC). The vapor compression systems were set at 18°C and 22°C in three main investigations: 1) only the vapor compression systems worked in the empty and hot-and-humid rooms; 2) only the floor cooling systems worked in the empty and hot-and-humid rooms; and 3) two combined refrigerating systems worked in the empty and hot-and-humid rooms. The energy consumption obtained from both compression systems was reported and analyzed. The room temperatures, room relative humidity, and evaporated water from the hot water vapor generators or the water boiling systems in both rooms were also revealed. The condensed water on the cooling floor was observed in the high relative humidity conditions in the hot and humid rooms. The power consumption information presented in this work can be used to calculate the important operating costs of the refrigerating systems for different operating conditions in agricultural product storage, including low and high relative humidity. Information from the condensed water observation on the floors can provide potential for floor cooling systems in agricultural product storage applications.

2. Experimental Setup

All experimental investigations were carried out in two identical test rooms that installed identical radiant floor cooling systems (Fig. 1), with one room equipped with the variable-speed compressor refrigerating system (VSC system) and another room equipped with the fixed-speed compressor refrigerating system (FSC system). Both test rooms were constructed in one temperature-controlled chamber; the chamber temperature was controlled at 25°C. Two thermocouples (SPL TS/101 trademark; thermocouples type K with the maximum measurable temperature at 400 °C) and hygrometers (DIXELL XH20P RANG trademark; 0 – 99%RH ±3%) were placed inside each storage to measure the return air and the supply air, and one thermocouple was placed outside each storage to measure the inlet air of the air-cooled condensing unit. There were two heat load conditions applied during the 2-hour investigation in each room: one was "no heat load" (turn off the water boiling system), and another was "heat loaded" from boiling water as well as the hot and humid products stored in the rooms. There were 3 cooling system investigations in each heat load condition: 1) using only vapor compression systems; 2) using only floor cooling systems; and 3) using combined refrigerating systems, for a total of 6 investigations in this work. Fig. 2 illustrates the steps of each investigation. In Step 1, setting temperatures of the traditional systems to 18°C or 22°C only when the traditional systems were investigated. In Step 2, turning on the cooling systems as turning on only the traditional systems in the first experiment, only the floor cooling systems in the second experiment, and both systems in the third experiment. In Step 3, tuning on the boiling systems only when the load was concerned. The vapor compression systems were set at 18°C and 22°C to find the effects of different setting temperatures on the observed parameters in all six investigations. The room temperatures, relative humidity, and energy consumption of the vapor compression systems were recorded as the investigation parameters in each investigation. All refrigeration systems were turned on for 30 minutes to stabilize the load inside the rooms before all parameters were recorded. All parameters were compared and analyzed to determine the indoor air conditions and the energy consumption of the simulated agricultural product storage equipped with the different cooling systems.

Fig. 1. The radiant floor cooling installation.

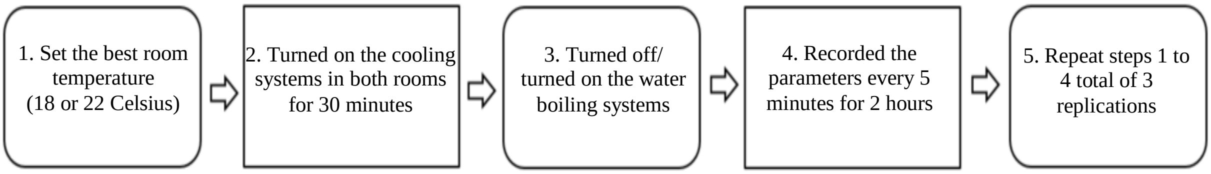
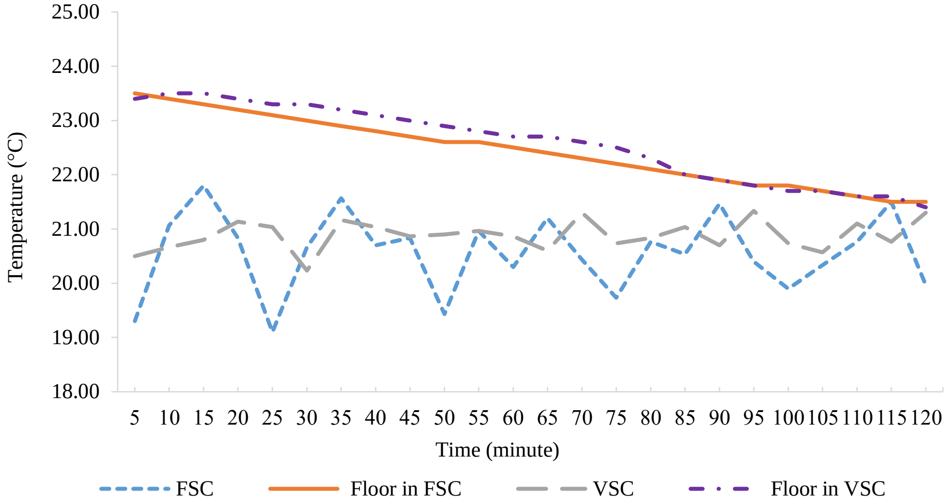


Fig. 2. Experimental investigation steps.

3. Results and Discussion

As the based conditions, room temperatures, relative humidity, and energy consumption of each refrigerating system in the no-heat-load room were first investigated. Since the radiant floor cooling systems and the vapor compression systems were turned on for 30 minutes, the initial room temperatures recorded from the former and latter systems were different. Fig. 3a shows the room temperatures of the single cooling system operations using only the FSC system, only the VSC system, and only the floor cooling systems working in two experimental rooms. It was found that the average room temperatures of the cooling systems using only the FSC and VSC systems set at 22°C were 20.57±0.71°C and 20.88±0.27°C, respectively. The average room temperatures using only the floor cooling systems were 22.43±0.62°C and 22.58±0.69°C, respectively. It could be seen that the individual operations of the FSC and VSC systems resulted in a better reduction in temperatures (lower temperatures) than using only the floor cooling systems. Furthermore, from the graphs' trend, it could be seen that the room temperatures conditioned by only the floor cooling systems were more stable than the room temperatures conditioned by the FSC and VSC systems. Fig. 3b revealed the relative humidity obtained from the rooms where the FSC and VSC cooling systems were set at 22°C. It was found that the average room %RH conditioned by using only the FSC and VSC systems was 64.42±4.50%RH and 63.28±0.81%RH, respectively. Therefore, it could be seen that the operations of the FSC and VSC systems resulted in close values of %RH, while the %RH of the VSC system room was more stable than that of the room using only the FSC system. Furthermore, from the graphs' trend, it could be seen that the room %RH using only the floor cooling systems was close to the %RH provided by the FSC and VSC systems, but they were less fluctuated.



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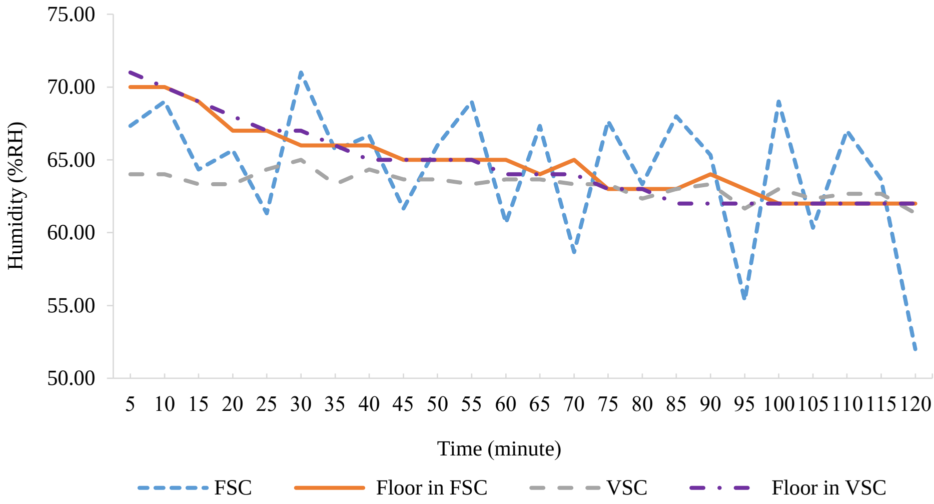
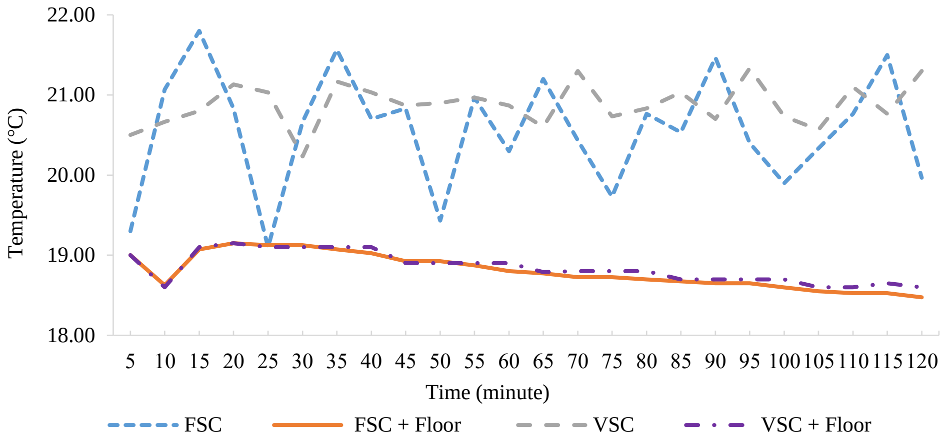


(b)

Fig. 3. Room (a) temperatures and (b) relative humidity provided by FSC, VSC, and radiant floor cooling systems in the no-heat-load rooms; the vapor compression systems set at 22°C.

Fig. 4a illustrates the room temperature comparisons among the room operations using only the FSC system, only the VSC system, and the vapor compression systems coupled with the floor cooling systems working in two experimental rooms. The average room temperatures of the coupled cooling systems using the FSC and VSC systems set at 22°C were 18.80±0.21°C and 18.85±0.19°C, respectively. Therefore, it was clearly seen that the room temperatures, when the combined cooling systems were operated, could be reduced, and the combined systems provided better room temperatures than those of the rooms using only the FSC or VSC systems. From the graphs, it could also be seen that the room temperatures provided by the coupled cooling systems were more stable than those provided by the single FSC and VSC systems. Fig. 4b demonstrates the relative humidity comparisons of the operations: the individual vapor compression systems and the combined cooling systems. The average room %RH of the combined systems with FSC and VSC systems set at 22°C were 67.75±3.11%RH and 65.75±5.13%RH, respectively. Notably, the average %RH of all cases was different, but all systems provided the %RH in the same range. The %RH values of the combined cooling systems were smoother than those of the single vapor compression systems.



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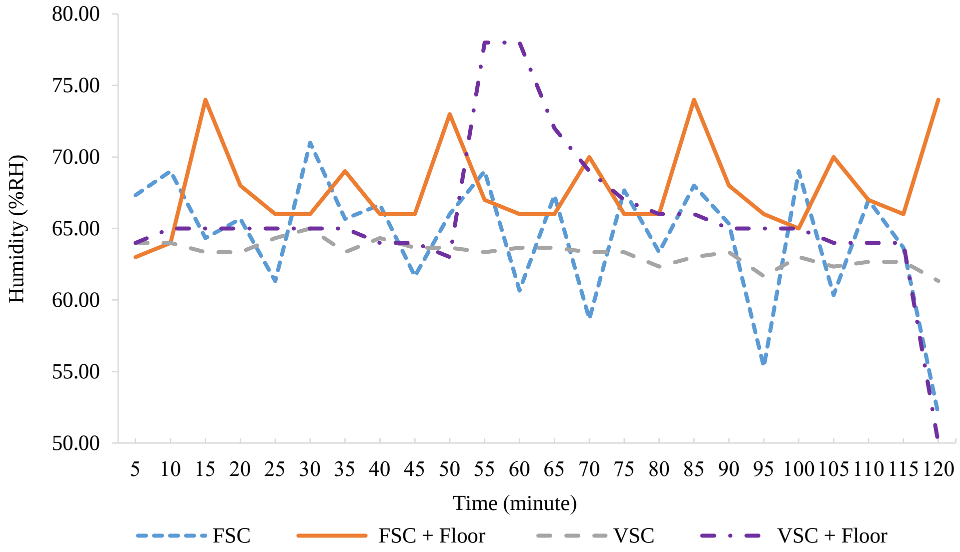
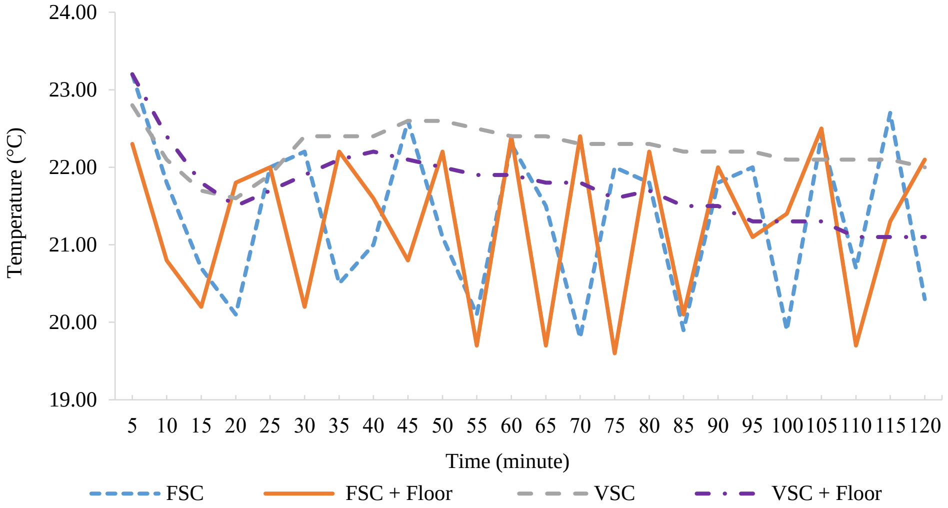


(b)

Fig. 4. Room (a) temperatures and (b) relative humidity provided by FSC, VSC, radiant floor cooling, and combined systems in the no-heat-load rooms; the vapor compression systems set at 22°C.

Since agricultural products can generate both sensible and latent heat loads inside their storage rooms, therefore, the heat loads were stimulated in the rooms as in the actual storage situations. The temperatures of the rooms with heat-loaded simulations and the compression systems set at 22°C were plotted in Fig. 5a. Noticeably, before the water boiling systems were turned on, the relative humidity of air was lower than 80%RH. On the other hand, when the water boiling systems were turned on, the relative humidity of air was higher than 80%RH or called high %RH. The results showed that the average room temperatures of the single compression systems (FSC and VSC systems) with high heat loads were 21.35±1.00°C and 22.24±0.27°C, respectively. Additionally, the average room temperatures of the combined cooling systems, the FSC and VSC systems coupled with the floor cooling systems, were 21.26±1.00°C and 21.74±0.47°C, respectively. It could be obviously noticed that the combined cooling systems could reduce the higher-temperature rooms better than using the individual compression systems. The graph also illustrated that the average room temperature delivered by the compression systems fluctuated. On the other hand, the temperatures delivered by the coupled systems when the floor cooling systems were applied were steady in both cases. The rooms had higher sensible and latent heat loads from boiled water, causing higher temperatures and humidity. The operations of the single vapor compression systems set at 22°C (Fig. 5b) resulted in the average room %RH at 86.71±6.72%RH and 85.92±2.60%RH, respectively. The average room %RH of the combined cooling systems was 85.50±3.92%RH and 85.13±2.59%RH, respectively. Noticeably, the combined cooling systems had a similar %RH as the single compression systems. But the room %RH of the combined cooling systems was more stable than that provided by the single compression systems in the rooms with high relative humidity, as conditions in the agricultural product storage.



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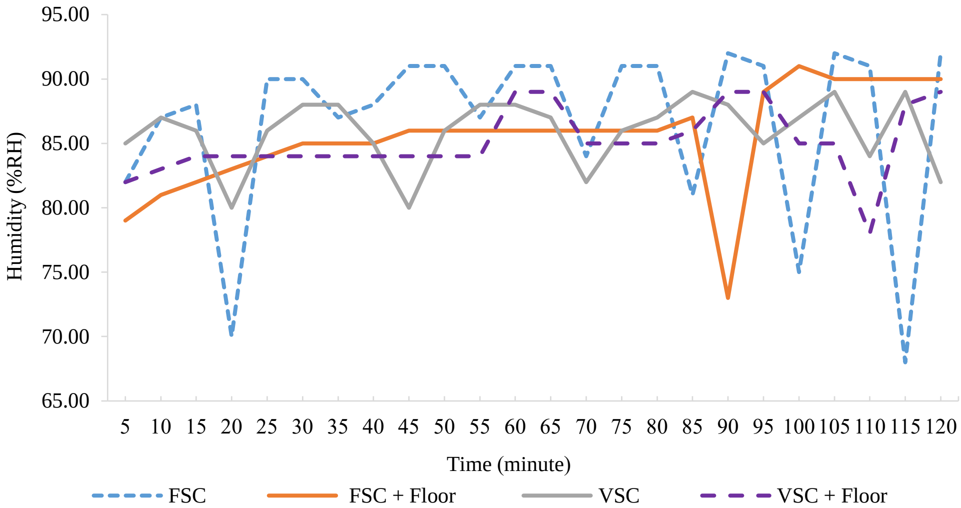
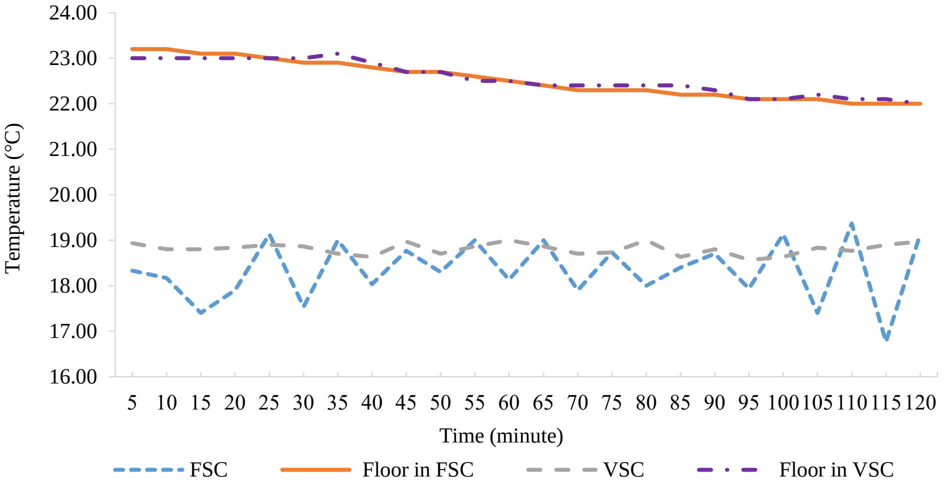


(b)

Fig. 5. Room (a) temperatures and (b) relative humidity provided by FSC, VSC, radiant floor cooling, and combined system in the heat loaded rooms; the vapor compression systems set at 22°C.

As agricultural product applications are everywhere in the world, each product requires suitable conditions—temperatures and relative humidity differently. Therefore, the compression-system operating temperatures varied in the current work. Fig. 6 and 7 show the temperatures of the cooling system operations set at 18°C in the no-heat-load rooms. It was found that the average room temperatures provided by only FSC and VSC systems were 18.34±0.66°C and 18.81±0.12°C, respectively. The average room temperatures using only the floor cooling systems in both rooms during the 2-hour operation were 22.53±0.41°C and 22.55±0.36°C, respectively. Visibly, the operations of the FSC and VSC systems resulted in a better reduction in temperatures than those provided by only the floor cooling systems, while the room temperatures provided by the latter systems were more stable than those from the compression systems. The average no-heat-load room %RH from the single FSC and VSC systems were 76.46±6.50%RH and

75.49±3.11%RH, respectively, as displayed in Fig. 6b. The average %RH of the rooms using only the floor cooling systems was 63.96±2.81% and 62.54±2.75%RH, respectively. The floor cooling system provided the same %RH range as in the previous %RH set since there was no difference in the floor cooling systems when the compression systems were set at 18°C and 22°C. Evidently, the single lower-temperature operations of the FSC and VSC systems had a higher %RH than the rooms using the floor cooling systems. Furthermore, from the graphs, the %RH of the rooms using only the floor cooling system was more stable than the %RH of the rooms using only the compression systems.



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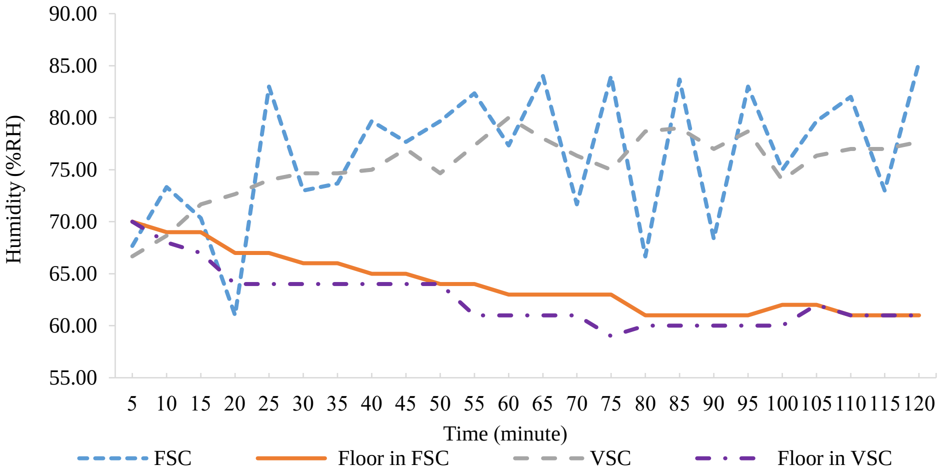
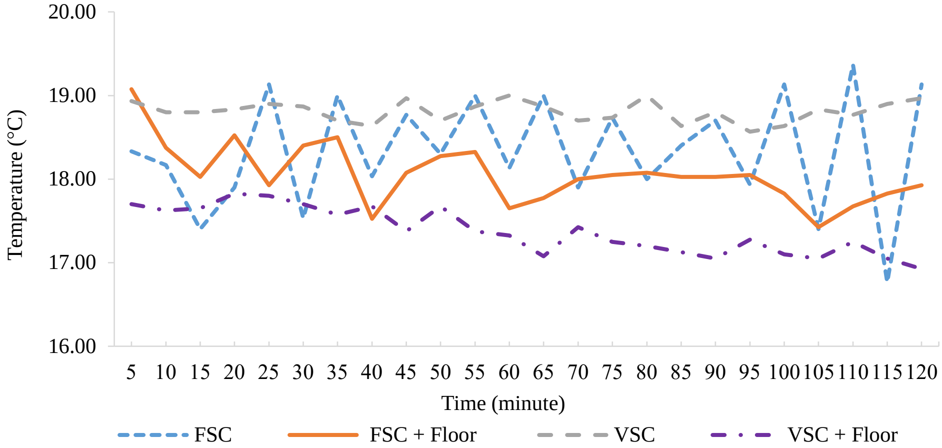


(b)

Fig. 6. Room (a) temperatures and (b) relative humidity provided by FSC, VSC, and radiant floor cooling systems in the no-heat-load rooms; the vapor compression systems set at 18°C.

Fig. 7a illustrates the average room temperatures of the combined cooling system using the FSC and VSC systems together with the floor cooling systems, which were 18.06±0.35°C and 17.38±0.27°C, respectively. Both combined cooling systems could reduce room temperatures better than rooms using only compression systems. From the graphs, the room temperatures of the combined cooling systems fluctuated, but they were in the same range. The average room %RH of the combined systems set at 18°C was 83.13±7.01%RH and 82.67±3.60%RH, respectively. It could also be noticed, as indicated in Fig. 7b, that the rooms using the combined cooling systems had a higher %RH than the rooms using only compression systems. The %RH ranges of both rooms using only compression systems were close.



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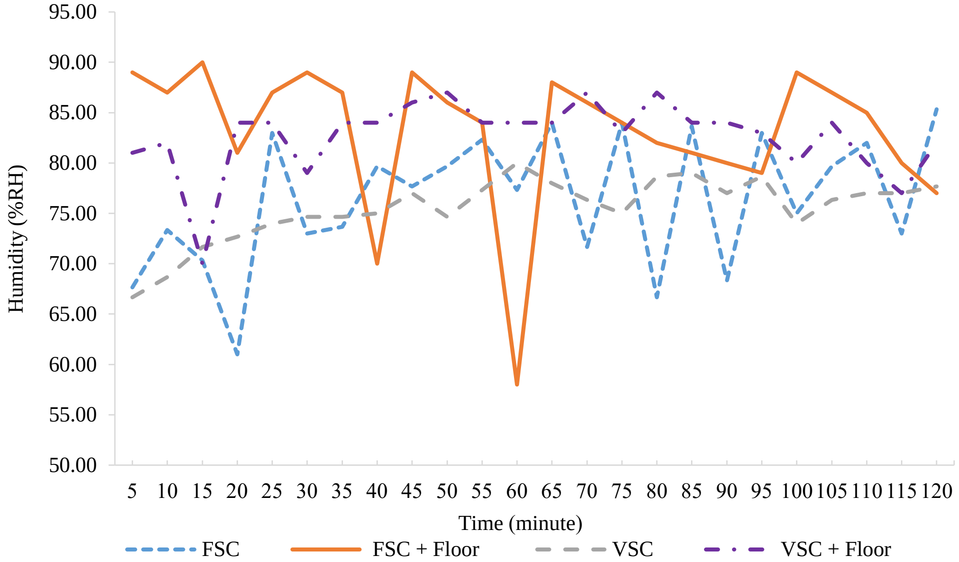

(b)

Fig. 7. Room (a) temperatures and (b) relative humidity provided by FSC, VSC, radiant floor cooling, and combined systems in the no-heat-load rooms; the vapor compression systems set at 18°C.

Fig. 8a compares the temperatures of the rooms where the compression systems were set at 18°C with high humidity from boiled water. The results showed that the average room temperatures were 19.75±0.53°C and 19.64±0.18°C, respectively. The average temperatures of the high-humidity rooms with the combined cooling systems were 17.77±0.52°C and 17.95±0.30°C, respectively.

It could be noticed that the combined cooling systems could reduce room temperatures with high humidity better than those provided by each compression system. The temperatures measured from the FSC System rooms fluctuated in the individual and combined operations. Clearly, the temperatures measured from the combined system rooms were steady in both cases. The results of the average %RH conditioned by only the compression systems in the hot and humid rooms as in traditional storage rooms for agricultural products were 84.32±6.92%RH and 84.58±1.74%RH, respectively (Fig. 8b). The average %RH of the rooms conditioned by the combined cooling systems was 81.54±9.23%RH and 83.13±3.97%RH, respectively. When the heat loads were applied in the rooms, all cooling systems had a close %RH. The %RH of the air inside the rooms using only the compression systems fluctuated the most. On the other hand, the %RH of the air inside the rooms using the combined systems was more stable in both cases.

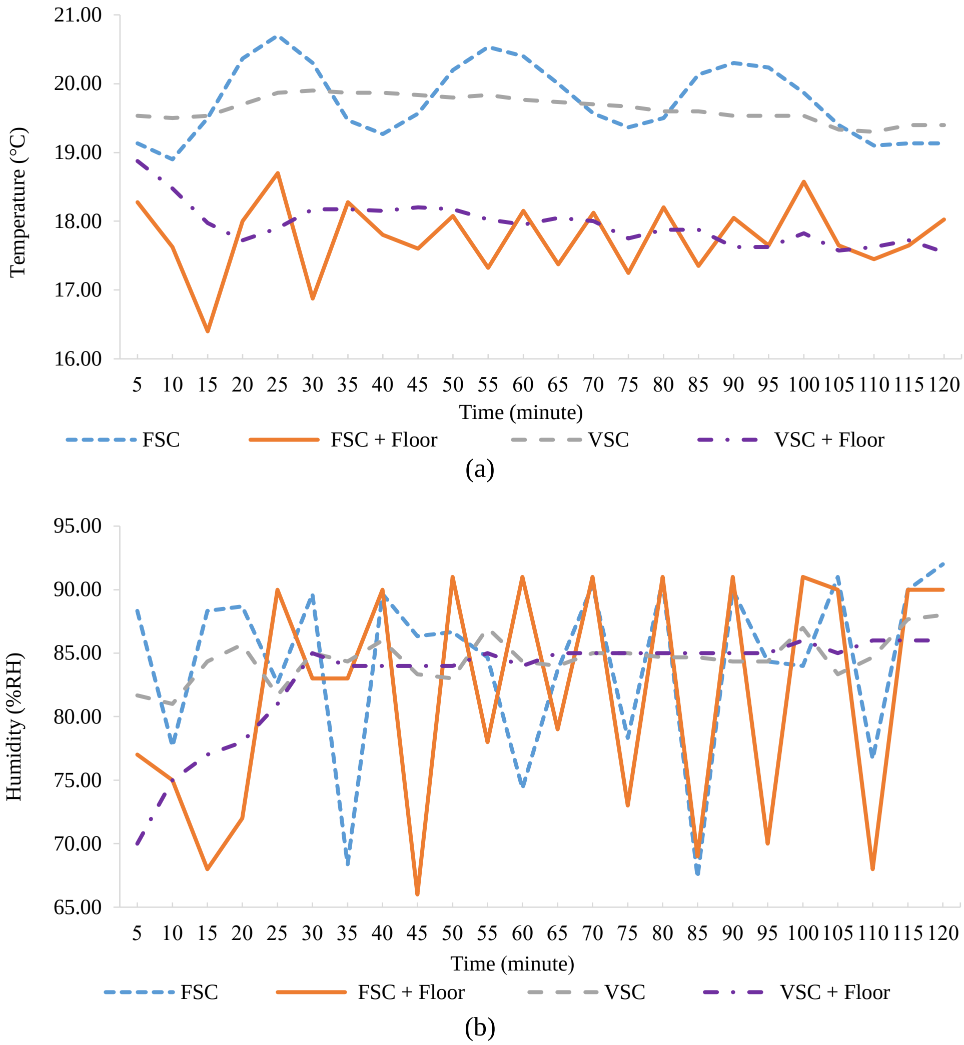

Fig. 8. Room (a) temperatures and (b) relative humidity provided by FSC, VSC, radiant floor cooling, and combined systems in the heat loaded rooms; the vapor compression systems set at 18°C.

The 12000-BTU water chiller was utilized in this work to produce chilled water at about 6°C, and the water was fed to the floor cooling systems at about 9°C. The water was chilled and collected beyond need because the water tank could fill 120 liters of chilled water, but the system required only 10 liters. Therefore, the water chiller consumed more electrical energy to chill 120 liters of water than the amount of electrical energy required to chill 10 liters of water. The electrical consumption of each system was reported in Fig. 9 and Table 1 when they were operated separately in the no-heat-load rooms. Obviously, the electrical consumption of the water chiller was constant. The electrical consumption of the FSC System was higher than that of the VSC System when the compression systems were set at 18°C and 22°C, respectively.

After the floor cooling systems were operated with the compression systems set at 18°C and 22°C, the energy index of the FSC system was reduced by 40.00% and 53.85%, respectively, as shown in Fig. 9 and Table 2. The energy index represents the energy consumption per cooling floor area. While the energy index of the VSC system was also reduced by 14.29% and 50.00%, respectively, the higher the operating temperature, the greater the reduction in electrical consumption. Apparently, adding the floor cooling systems at the low operating temperature reduced the energy index of the FSC system better than that of the VSC system. However, adding the floor cooling systems at the high operating temperature reduced the energy index of the FSC system to that of the VSC system. The threshold for switching on and off the FSC compressor was in a range of ±1.5°C. When the FSC compressor was turned on or called starting mode, the FSC compressor consumed energy more. In normal operating state, the FSC compressor took an average electrical current of 4.8 A while it took an average electrical current of 6.9 A in each starting mode.

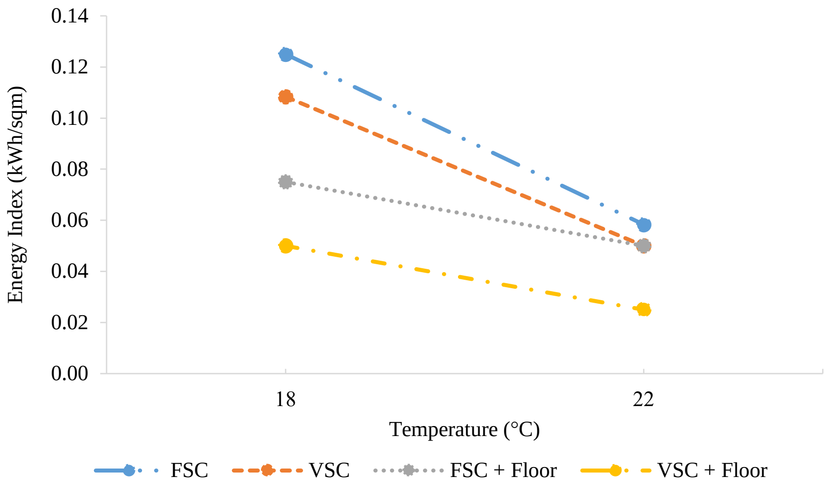

Fig. 9. Average energy index varied with the set temperatures of the vapor compression systems obtained from FSC, VSC, and combined systems in the no-heat-load rooms.

Table 1: The energy index of the cooling system using the fixed-speed compressor, variable-speed compressor, and floor cooling systems.

The vapor-compression-system set temperatures	Energy index (kWh/sqm) during 2 hours of the operation		
	Only FSC	Only VSC	Water Chiller
18°C	0.50	0.43	0.95
22°C	0.23	0.20	0.95

Table 2: The energy index of the cooling system using the single vapor compression and combined systems.

The vapor-compression-system set temperatures	Energy index (kWh/sqm) during 2 hours of the operation		% Change in energy index	
	Floor Cooling + FSC	Floor Cooling + VSC	Floor Cooling + FSC	Floor Cooling + VSC
18°C	0.50 0.30	0.43 0.20	40.00%	14.29%
22°C	0.23 0.20	0.20 0.10	53.85%	50.00%

Finally, when the heat loads from boiling water were added to the rooms, the results were expressed in Fig. 10 and Table 3 for both operating temperatures of 18°C and 22°C. Adding the floor cooling systems and increasing the heat and humidity in the rooms reduced the energy index of the FSC system by 22.22% and 40.00%, respectively, while the energy index of the VSC system was also reduced by 28.57% and 50.00%, respectively. Undoubtedly, adding the floor cooling systems in both heat-loaded rooms decreased the electrical consumption of the VSC system better than that of the FSC system. All results proved that the floor cooling systems enhanced the efficiencies of the vapor compression systems in both operating temperatures (18°C and 22°C) and both room conditions (no heat load and heat load).

The energy index of the water chiller was higher than that of the vapor compression systems because the chiller operated most of the experiment period to produce an over-demand amount of water. The electrical consumption of the water chiller was constant in each heat load condition. The constant electrical consumption implied that the radiant floor cooling systems took the heat out of the no-heat load and heated load rooms constantly.

Because condensed water was one of the main concerns about utilizing the radiant floor cooling system in the high relative humidity conditions of agricultural product storage, condensed water in the heated load room was observed. Apparently, there was no condensed water on the cooling floor. This could be caused by the vapor compression system forcing humid air inside the refrigerated space. Comparing the two vapor compression systems, the VSC system could create less fluctuated air conditions inside the storages. Moreover, the radiant floor cooling systems could apparently provide a more stable temperature and relative humidity of the air inside the storages under different load conditions.

Although the radiant floor cooling systems assisted the vapor compression systems in consuming less electrical power in the combined systems, the combined systems were suitable for places where chilled water was available. On the other hand, if chilled water is available with no operation cost, such as solar water chillers, the radiant floor cooling systems will take the heat with low operating consumption and enhance the performance of the vapor compression systems.

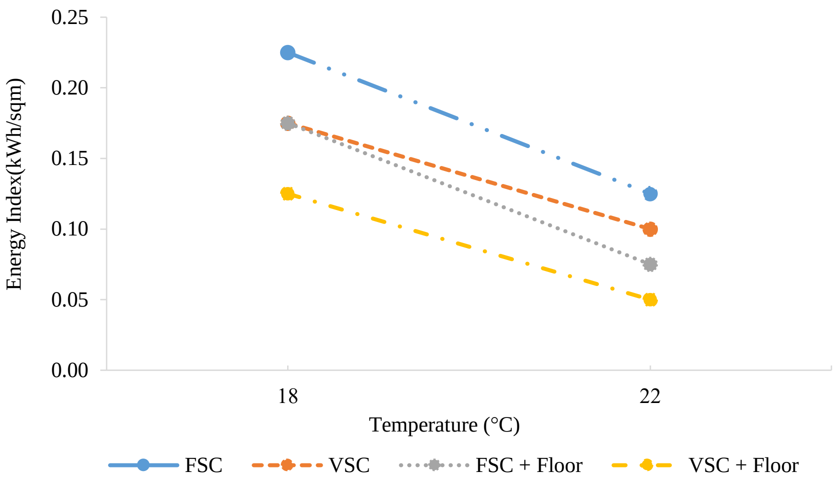

Fig. 10. Average energy index varied with the set temperatures of the vapor compression system obtained from FSC, VSC and combined systems in the heat loaded rooms.

Table 3: The energy index of the cooling system using the combined systems in the heat loaded rooms.

The vapor-compression-system set temperatures	**Energy index (kWh/sqm) during 2 hours of the operation**		**% Change in energy index**	
	Floor Cooling + FSC	**Floor Cooling + VSC**	**Floor Cooling + FSC**	**Floor Cooling + VSC**
18°C	0.90 0.50	0.70 0.20	22.22%	28.57%
22°C	0.79 0.39	0.60 0.48	40.00%	50.00%

4. Conclusion

Since there was available research on the radiant floor and traditional cooling systems for commercial areas, the radiant floor cooling systems presented their advantages in energy saving and uniform temperature distribution. Therefore, the radiant floor cooling systems have potentials to be used in storages for agricultural product. The radiant floor cooling systems can be used with traditional vapor compression systems in storage to reduce the latter's energy consumption. The objectives of this work were to investigate and find the temperatures and relative humidity of the air inside the storages, as well as cooling-system energy consumption. Two identical storage rooms were equipped with radiant floor cooling systems, while one room installed the fixed-speed compressor (FSC) system, and another room installed the variable-speed compressor (VSC) system. The vapor compression systems were set at 18°C and 22°C, and two heat conditions, no heat load and heat loaded, were examined to find the effects of different operating setups. When the single vapor compression systems were determined, the VSC system consumed less energy than the FSC system. The results showed that the radiant floor cooling systems not only assisted both vapor compression systems to consume less energy, but the floor cooling systems also created less fluctuating conditions. After the floor cooling systems were operated with the compression systems set at 18°C and 22°C, the energy index of the FSC system was reduced by 40.00% and 53.85%, respectively. While the energy index of the VSC system was also reduced by 14.29% and 50.00%, respectively, the higher the operating temperature, the greater the reduction in electrical consumption. Apparently, adding the floor cooling systems at the low operating temperature reduced the energy index of the FSC system better than that of the VSC system. The combined systems were highly recommended to be used in storages containing products that were sensitive to fluctuated temperatures and relative humidity, such as ready-to-eat, fresh fruit, and food products.

Nomenclature

FSC	Fixed Speed Compressor
VSC	Variable Speed Compressor

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