We studied a shipping container integrated with phase change material (PCM) based thermal energy storage (TES) units for cold chain transportation applications. A 40 ft container was used, which was installed with ten plate-like TES units containing PCM and a charging loop. An appropriate PCM was selected for meeting the requirement of the transportation of fresh vegetables (7-12°C). The charging loop was linked to a separate charging facility via quick coupling valves. The discharging performance of the container under dynamic conditions was investigated. The COP of the system was estimated to be 1.73. Economic analyses showed that energy and operation costs of the PCM-based container were, respectively, 71.3% and 85.6% lower than the same container but powered by a diesel engine (called reefer container). The results also showed that the PCM-based container was able to maintain not only the temperature range (7-12°C) but also the humidity range (85-95%), leading to better quality and longer shelf-life of the goods.

1. Introduction

Currently, cold chain transportation relies on vapour compression refrigeration cycle which is driven by diesel engines [1]. Such technology is expensive due to both high fuel and maintenance costs; it also emits a significant amount of CO₂ and particulate matter thus contributing to global warming.

Taking the advantage of the high energy density [2] and the constant temperature during the phase transition [3], the PCM-based TES is feasible to provide cooling without a constant energy supply. This makes the TES an appropriate method to balance the demand and supply of energy. Besides, the TES can integrate renewable energy well [4]; therefore, it has become ever more attractive in recent years [5].

Some recent studies are using the PCM-based TES for cold chain applications. Michel et al. [6] experimentally and numerically studied a composite layer of PU-PCM foam dedicated to refrigerated vehicles. It was reported that the heat flux across the wall during the “road delivery period” could be reduced by 18% by using the PCM. A refrigeration system incorporating PCM was proposed to achieve the low temperature required for refrigerated trucks [7, 8]. The TES unit was charged by a mechanical refrigeration unit located off the vehicle. When the truck was on duty for delivering products, the PCM discharged and provided cooling. It was concluded that the cost of the PCM integrated refrigeration unit was 86.4% less than conventional systems. An improvement in the temperature control with lower temperature fluctuations and the reduced noise level was also reported.

One can see from the above work when integrating the TES with the conventional cooling system an energy efficiency improvement and the reduction in temperature fluctuations can be achieved. In this work, we introduced the PCM-based TES to the shipping container for cold chain transportation which aimed to investigate the feasibility of the real applications. There is only limited research on integrating the PCM-based TES with shipping containers. Sepe et al. [9] proposed a concept for a 20-feet International Organization Standardization (ISO) container with twelve
2. Experimental Set-up

2.1. Material. The PCM RT 5 HC is from Rubitherm Company [10]. It melts at 5°C with a latent heat of 220 kJ/kg. The main thermo-physical properties of the PCM are listed in Table 1.

2.2. Thermal Energy Storage Plate. The TES plate was constructed on the embedded finned tubes which acted as the charging fluid loop. The outer size of a single TES plate is 1800(L) * 1000(W) * 100(H) mm (see Figure 1).

For each plate, 126 kgs of PCM were filled. Three thermocouples were installed inside each cold TES plate. The location of the thermocouples is shown in Figure 1, with an immersion depth of 0.05 m.

2.3. Container. The dimensions of the container are shown in Figure 2, with 100 mm thickness of polyurethane foam inside the walls as insulation material. Up to 10 plates were installed inside each container, with 9 of them located on the ceiling, and one was installed at the front of the internal wall. There are eight sensors located in two layers, with the height of the first layer (numbers 1, 3, 5, and 7) and the second layer (numbers 2, 4, 6, and 8) from the bottom at 1.8 m and 0.9 m, respectively. In the axial perspective, the sensor was annotated with the distance from the frame edge opposite the door. Number 5 and 6 sensors were attached on the middle of the sidewall. The last two sensors, annotated as numbers 1 and 2, were fixed on the frame edge opposite the door. One sensor was placed outside the container to get the ambient temperature and relative humidity. For the dynamic experiments with carrying loads, another three sensors were inserted into the items. The three sensors were installed at the same level (1.2 m to the container bottom), with numbers 9, 10, and 11 having a distance of 12 m, 8 m, and 4 m from the door, respectively.

A data logger system (Hwa Innovate Technology Co. Ltd) was used to record the temperature and relative humidity. The temperature sensors (RTD (PT100) probes) and the RH sensors showed an uncertainty of 1% and 3%, respectively. The internal photo of the shipping container is shown in Figure 3.

2.4. Charging Process. The charging unit mainly includes an electricity-powered chiller from BITZER, and a centrifugal pump which is used to circulate the HTF between the charging unit and the container. The HTF tank is used to store the pre-cooled heat transfer fluid. It was filled with 14 m³ EG-water solution that is identified as the HTF shown in Table 2.

By connecting the container with the charging unit through the charging loop, the HTF between the tank and the plates was circulated. Inside the plates, the cold HTF transferred the cold energy to PCMs. The temperature of the outlet and the recirculated HTF was monitored by the wireless data logger system which was provided by Hwa Innovate Technology Co. Ltd. The RTD (PT100) probe with uncertainly at 1%. The flowrate meter with 2% uncertainty was employed to obtain the flowrate of the HTF. The completion of the charging was indicated by the temperature of PCMs which can be obtained by the thermocouples.

3. Performance Index

3.1. Discharging Time. Discharging time is defined as the period of the inside temperature of the container rising from 7 to 12°C. This is because most of the fruits and vegetables can retain freshness within this temperature range [11].

3.2. System COP. The total energy released by heat transfer fluid (HTF, Ethylene glycol-water solution, Q_{EG}) is given as Eq. (1):

\[ Q_{EG} = c_{p,EG} \cdot m_{EG} \cdot (T_{s,EG} - T_{i,EG}). \]  

where \( m_{EG} \) is the HTF mass flow; \( c_{p,EG} \) is the specific heat capacity of the HTF; and \( T_{s,EG} \) and \( T_{i,EG} \) are the HTF temperature at the return and inlet of the charging unit, respectively.

Except for the heat loss to the ambient, the energy transferred by HTF is adsorbed by the PCMs, the moist air inside the container and the aluminium frame of the TES plates. The energy stored by PCMs (Q_{PCM}) can be given as Eq. (2):

\[ Q_{PCM} = m_{PCM} \cdot [c_{p,PCM} \cdot (T_{s,PCM} - T_{i,PCM}) + \Delta H_{PCM}], \]  

where \( m_{PCM} \), \( \Delta H_{PCM} \), and \( c_{p,PCM} \) are the mass, latent heat capacity, and specific heat capacity of the PCM, respectively; \( T_{s,PCM} \) and \( T_{i,PCM} \) are the temperatures of PCM at the end and initial stage of the experiments.

The energy transferred to the aluminium frame of the TES plates, Q_{Al}, can be achieved by Eq. (3):

\[ Q_{Al} = m_{Al} \cdot c_{p,Al} \cdot (T_{s,Al} - T_{i,Al}), \]
where $m_{Al}$ and $c_{p,Al}$ are the mass and specific heat capacity of aluminium, respectively. $T_{c,Al}$ and $T_{i,Al}$ are the temperatures of aluminium at the end and initial stage of the experiments.

The energy absorbed by the moist air ($Q_{ma}$) is mainly consisted of two parts, with the first part being dry air ($Q_d$) and the second part being condensed water ($Q_w$). The $Q_{ma}$ can be obtained through Eqs. (4)–(6) below.

$$Q_{ma} = Q_d + Q_w,$$  \(4\)

$$Q_d = m_d \times c_{p,d} \times (T_{c,d} - T_{i,d}),$$  \(5\)

$$Q_w = m_w \times \Delta H_w,$$  \(6\)

where $m_d$ and $c_{p,d}$ are the mass and specific heat capacity of
Table 2: Comparison of the energy and economic performance of the TES and diesel-powered container.

<table>
<thead>
<tr>
<th>Properties</th>
<th>The diesel-powered</th>
<th>The TES-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery distance (km)</td>
<td>2362</td>
<td></td>
</tr>
<tr>
<td>Delivery duration (hour)</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Power consumption (kW)</td>
<td>5.4 [14]</td>
<td>1.55</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>Diesel(53L)</td>
<td>Electricity(82kWh)</td>
</tr>
<tr>
<td>Diesel consumption (L/h)</td>
<td>1 [15]</td>
<td>0</td>
</tr>
<tr>
<td>Diesel price($/L)</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Electricity price($/kWh)</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Diesel cost ($)</td>
<td>63.65</td>
<td>0</td>
</tr>
<tr>
<td>Electricity cost ($)</td>
<td>0</td>
<td>9.02</td>
</tr>
<tr>
<td>Operation cost reduction</td>
<td></td>
<td>85.6%</td>
</tr>
</tbody>
</table>

where $Es$ is the energy saving, $PDiesel$ and $PPCM$ are the power consumption of diesel-powered reefer container and the TES-based container, respectively.

The system COP for the dynamic operation carrying item can be calculated by Eq. (7).

$$COP = \frac{Q_{PCM} + Q_{Al} + Q_{ma} + Q_{EG,inside}}{W}$$ (7)

where $W$ is total electricity consumption during the charging process; $Q_{PCM}$, $Q_{Al}$, $Q_{ma}$, and $Q_{EG,inside}$ are the cold energy released by TES units (PCMs and aluminium frame), the internal moist air, and the sensible cold energy of HTF inside left inside the charging loop during the cooling process. They can be calculated by Eqs. (1)–(6).

3.3. The Energy Saving and Cost Reduction. The energy saving of the PC-based TES container compared with that of diesel-powered reefer container can be obtained by Eq. (8).

$$Es = \left(\frac{P_{Diesel} - P_{PCM}}{P_{Diesel}}\right) \times 100\%,$$ (8)

where $Es$ is the energy saving, $P_{Diesel}$ is power consumption of diesel-powered reefer container, while $P_{PCM}$ is the power consumption of the PC-based container presented in this study.

The cost reduction of the PC-based TES container compared with that of diesel-powered reefer container can be calculated by Eq. (9).

$$CR = \left(\frac{C_{Diesel} - C_{PCM}}{C_{Diesel}}\right) \times 100\%,$$ (9)

where $CR$ is the cost reduction, $C_{Diesel}$ is the operation cost of a diesel-powered reefer container, while the $C_{PCM}$ is the operation cost of the PC-based container presented in this study.

4. Results and Discussion

The container was loaded with 22 tons of grapes and was transferred from Dunhuang to Chengdu, China, on 03/10/2018–06/10/2018 by road delivery. The loading of grapes into the container was completed at point A in Figures 4(a) and 5(a). The delivery distance and duration is 2362 km and 53 hours, see point B to C. The time evolution of the temperature and RH at the axial and vertical direction within the container can be seen in Figures 4 and 5, respectively.

4.1. Time Evolution of the Temperature and RH of the Container. Figures 4(a) and 4(b), and Figures 5(a) and 5(b) presented the time evolution of the temperature and relative humidity of the loaded container in the axial and the vertical direction, respectively. The temperature (T8) near the door side is the highest. However, in the perspective of the overall temperature distribution, the maximum temperature gap between the sensors is limited to ~2°C which indicates the uniformity of the overall temperature distribution. Besides, one can see that the temperatures close to the door are more sensitive to the door opening. In Figure 4(a), the T8 which is near the door shows the highest temperature change which is from 7°C to nearly 25°C.

By comparing Figures 4(b) and 5(b), the internal relative humidity of the container was found to be between 85% and 95%. The high relative humidity is helpful to keep the freshness of the carrying items.

4.2. Time Evolution of the Temperature and RH inside the Item. The time evolution of temperature inside the carrying items (Figure 6) showed that, during the whole delivery period, the temperature rose slightly until the completion of the delivery. When arriving at the destination, the temperature increased sharply after the doors were opened for unloading. One can notice that there was no obvious fluctuation of temperature in the process of transportation, which is beneficial to keep the freshness of the carrying items. Besides, the relative humidity inside the grapes was nearly 100% which means there is no risk of causing excessive dehydration. Hence, the PC-based container performs a better temperature and humidity control compared that of the conventional refrigeration container which faces temperature fluctuations [12] and excessive dehydration [13] issues.

4.3. The System COP. The system COP for the dynamic operation carrying item can be calculated by Eq. (7). The total electricity consumed during the charging process is 82 kWh. It was found that the system COP was 1.73.

4.4. The Energy and Cost Reduction. Table 2 shows the energy and economic analyses of the diesel-powered container and the PC-based container. The electricity consumption of the PC-based TES container was obtained through the electric meter.
The average power consumption of a PCM-based TES container is 1.55 kW, compared with that of the diesel-powered container, and the energy consumption was decreased by 71.3%, which is calculated by Eq. (8). Based on the average electricity tariff and diesel price in China, the cost can be reduced by 85.6%. This indicates the profitable benefit of the PCM-based TES container in the perspective of operation. The payback period was not included in this study as there is still a lack of yearly operations of the newly proposed container.

Both the electricity price and the operating strategy affect the economic performance of the PCM-based container. More profits could be obtained if the system is applied in a location with a peak-load shifting mode.
5. Conclusions

This work investigated the performance of a phase change material (PCM) based shipping container for cold chain transportation. The road test performance including the cooling duration and coefficient of the system (COP) of the container carrying items has been presented. Both energy and economic analyses were performed for comparing the diesel-powered and the PCM-based container scenarios in terms of energy consumption and operational cost. It was found that the system COP was 1.73 with the power and operation cost reduction at 71.3% and 85.6% when compared with the diesel-powered reefer container. This indicates the profitable benefit of the PCM-based TES container in the perspective of operation. Furthermore, the container can maintain at a low temperature without an external power supply which enables the container to be transferred flexibly. The improved flexibility and performance enhancement allow the container to be feasible for applications.

Nomenclature

$c_p$: Specific heat capacity (kJ kg$^{-1}$ K$^{-1}$)
$H$: Latent heat (kJ kg$^{-1}$)
$m$: Mass flow rate (kg s$^{-1}$)
$t$: Time
$m$: Mass
$T$: Temperature (°C K$^{-1}$)
$v$: Velocity (m s$^{-1}$)
$\rho$: Density (kg m$^{-3}$)
$Q$: Energy (kJ)
$W$: Electrical power (kJ)
$: US dollar.

Subscripts

PCM: Phase change material

$\text{T }_{\text{Ambient}}$: Ambient temperature
$\text{T }_9$, $\text{T }_10$, $\text{T }_11$: Temperatures of items
$\text{RH }_9$, $\text{RH }_10$, $\text{RH }_11$: Relative humidity of items
$\text{T}_{\text{Ambient}}$: Ambient relative humidity

Data Availability

The [DATA TYPE] data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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