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Evaluation of PCM Thermal Storage Demonstration System for Cold Storage

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Abstract

A phase change material (PCM) thermal storage system incorporated with an ammonia refrigeration system has been designed, constructed and tested on a commercial scale on a farm. A central ammonia refrigeration plant is used to cool a heat transfer fluid providing cooling for large cold-storage facilities capable of storing up to 3,000 tonnes of produce. During off peak periods the plant is used to freeze a PCM thermal storage facility. During daytime operations, the refrigeration plant is cycled off and the heat transfer fluid cooled by the PCM thermal storage system.

The most commonly used PCM in such applications is ice, which has excellent thermal storage characteristics. Yet heat transfer fluid temperatures of around 1°C to 2°C are only possible as the melting point of water is 0°C. Instead, the PCM used in this refrigeration system is a specialised salt-based product designed to operate in a unique tank which uses enhanced heat transfer techniques, developed by the University of South Australia with Glaciem Cooling Technologies. It can provide heat transfer fluid temperatures of around -6°C to -8°C, making it ideal for food storage where room temperatures are typically around -1°C to 3°C.

The new refrigeration plant at Parilla Premium Potatoes located in South Australia was commissioned in July 2013, with the PCM plant commissioned the following March. Monitoring data shows that the system was able to shift the electricity load from the peak to off-peak electricity period using PCM. In addition, testing after one year has shown that the PCM has not degraded.

It has been successfully demonstrated that a PCM thermal storage system can be used to shift the electricity load for cold storage from peak to off-peak periods.

1. Introduction

Refrigeration is the single biggest electricity consuming class of technology in Australia (Brodribb & McCann 2013). There are more than 45 million individual pieces of refrigeration equipment operating in Australia that consumed more than 22 per cent of all electricity used nationally in 2012. The total greenhouse gas emissions as a result of energy consumed to power these systems is estimated to be equivalent to more than 10 per cent of Australia's greenhouse emissions. Thermal storage for refrigerative cooling can make refrigeration systems operate more efficiently during the night and also can take advantage of the cheap electricity available during the off-peak electricity period (Bruno et al. 2014).

Australia's ageing electricity infrastructure requires significant investment. The most sensitive part of the system is peak demand, which is primarily caused by summer cooling and refrigeration (Fan & Hyndman 2011). Peak demand has been increasing precipitously over the past decade; for example, 50% of the electricity infrastructure in South Australia is used for 5% of the time, resulting in the most expensive electricity in the country, and is reflected in the pricing of off-peak tariffs at less than half of those in peak periods. Advances in thermal storage can bring the prospect of significant load shifting, with consequent improvements to the productivity of the electricity sector and reduced pressure to allocate scarce resources to the upgrading of infrastructure capacity.

Parilla Premium Potatoes is one of South Australia's leading potato, onion and carrot growers. It produces more than 55,000 tonnes of fresh produce annually for both local and international markets. The company has expanded significantly over the years and has large cool-storage facilities (Figure 1) capable of storing up to 3,000 tonnes of produce.

Figure 1. Vegetables in pallets in a cold room.

In 2012, Parilla made the decision to upgrade its 14-year-old R22 refrigeration system. It was decided to replace this with a central ammonia (R717) refrigeration plant which cooled a heat transfer fluid providing cooling for five cold storage rooms. Although the capital investment for adding PCM thermal storage was 51 per cent more than other choices without PCM, the pay-back period, based on energy consumption, was less than three years. So a PCM thermal storage facility was incorporated into the system, whereby the plant would be used to freeze the PCM during off-peak periods. During daytime operations, the plant would be cycled off and the heat transfer fluid cooled by the PCM.

The most commonly used PCM in such applications is ice, which has excellent thermal storage characteristics. Yet heat transfer fluid temperatures of around 1°C to 2°C are only possible as the melting point of water is 0°C (Liu et al. 2012). Instead, the PCM used in the Parilla refrigeration system is a specialised salt-based product designed to operate in a unique tank which uses enhanced heat transfer techniques, developed by the University of South Australia and commercialised through Glaciem Cooling Technologies. It can provide heat transfer fluid temperatures of around -6°C to -8°C, making it ideal for food storage where room temperatures are typically around -1°C to 3°C.

The new refrigeration plant at Parilla was commissioned in July 2013 and the PCM storage facility commissioned in March 2014.

2. System Operation

The PCM thermal storage facility (Tay et al. 2012; Castell et al. 2011) consists of 4 tanks each with a 60 kW rated cooling capacity for a maximum of 12 hours. The facility uses a low viscosity heat transfer fluid significantly reducing the required pumping power. The system was originally designed to operate on a 12 hour peak and off-peak discharge and charge cycle. However, with a shift to an electricity demand tariff, the system operation was changed to shift 8 hours of compressor load to the off-peak period. The peak period for the demand tariff is defined as from noon to 8 pm on business days, December to March. The off peak period is outside this time.

Figure 2. Thermal storage facility consisting of 4 tanks filled with PCM.

Throughout 2014, the refrigeration plant with a rated cooling capacity of 280 kW was adequately providing cooling for the load presented by the product within the cold rooms. The thermal storage system was regularly engaged within the system and almost daily subject to charging and discharging. However, due to a range of issues, the thermal storage system was unable to operate under design conditions. One of the major problems was that the refrigeration plant had to be undersized due to the peak power capacity available on the farm. This meant that the compressor cooling capacity was insufficient to charge the PCM and cool the rooms simultaneously. The other major issue was that it was decided to install an additional cold store room, dramatically increasing the load on the refrigeration system and preventing sufficient capacity for complete charging of the PCM.

To overcome these issues, the rooms were disengaged during charging from midnight to 6 am, to maximise charging opportunity. This had no impact on product which was already cooled to temperature. In addition, the additional room was removed from the load in November 2014 in order to carry out testing on the PCM thermal storage facility.

3. Results

Tables 1 and 2 summarise the daily performance of the storage system for some of the days from December 2014 to February 2015. The testing conducted was designed to demonstrate the capability of the existing refrigeration system and thermal storage system, to meet the requirements of the demand tariff under the load conditions tested. In summary the system can meet demand reduction requirements, however a lack of charging capacity was observed resulting in a gradual loss of discharging capacity in the thermal storage system.

In Table 1 the storage system successfully charged and discharged for 7 consecutive days from the 16th to 22nd December. The days following this period, the storage system delivered a reduced discharge capacity. The average discharge cooling capacity was 43.5 kW per tank, and the average discharged energy was 48% of designed capacity. Table 2 shows 11 consecutive days of operation from the 14th to 24th January, followed by a reduced discharge on the 25th January. Over the 11 days the average discharge capacity was 44 kW per tank, representing 51% of the energy capacity of the thermal storage system. On the 26th January an extended charge of the PCM system was performed. This was followed by four successful days of charge/discharge, after which a further extended charge was conducted. Subsequently, 6 consecutive cycles were conducted, concluding with an extended discharge. After an extended charge a second extended discharge test was conducted.

The demand tariff requires 8 hours of load to be shifted during business days. The number of consecutive successful charge/discharge cycles reached 11, demonstrating that the storage system is capable of achieving this goal. To overcome the gradual loss of charge, an extended charge was conducted to demonstrate that this can fully charge the storage system. This extended charge could be readily achieved on weekends, enabling the storage system to meet discharging requirements during the week. Extended discharge was conducted to identify the maximum discharge capacity of the storage system. The average cooling capacity over 13 hours was 39 kW per tank, resulting in 71% of the discharge capacity being proven. On the 6th February the storage system was not fully charged and on the 8th February there was insufficient load to fully discharge. Therefore the storage system has greater capacity than tested.

Table 1. Daily charge/discharge performance of PCM system in December 2014.

Cycle No.	Discharge Date	Total discharge, kWhr	Discharge hours	Average discharge rate, kW	Discharge/ Capacity Ratio
1	16/12/2015	1259	8	157	0.44
2	17/12/2015	1325	8	166	0.46
3	18/12/2015	1293	8	162	0.45
4	19/12/2015	1103	8	138	0.38
5	20/12/2015	1628	8	203	0.57
6	21/12/2015	1742	8	218	0.60
7	22/12/2015	1384	8	173	0.48
8	23/12/2015	1250	5	250	0.43
9	24/12/2015	883	3	294	0.31
10	25/12/2015	889	3	296	0.31
11	26/12/2015	973	4	243	0.34

Table 2. Daily charge/discharge performance of PCM system for some days in Jan/Feb 2015.

Cycle No.	Discharge Date	Total discharge, kWhr	Average Discharge rate, kW	Discharge hours	Discharge/ Capacity Ratio
1	14/01/2015	1920	175	11	0.67
2	15/01/2015	1399	175	8	0.49
3	16/01/2015	1307	163	8	0.45
4	17/01/2015	1100	122	9	0.38
5	18/01/2015	1010	126	8	0.35
6	19/01/2015	1636	205	8	0.57
7	20/01/2015	1416	177	8	0.49
8	21/01/2015	1618	202	8	0.56
9	22/01/2015	1690	211	8	0.59
10	23/01/2015	1415	177	8	0.49

11	24/01/2015	1683	210	8	0.58
12	25/01/2015	1440	240	6	0.50
13	27/01/2015	1752	219	8	0.61
14	28/01/2015	1627	203	8	0.57
15	29/01/2015	1352	169	8	0.47
16	30/01/2015	1441	180	8	0.50
17	1/02/2015	1685	211	8	0.59
18	2/02/2015	1454	182	8	0.50
19	3/02/2015	1265	158	8	0.44
20	4/02/2015	1569	196	8	0.54
21	5/02/2015	1375	172	8	0.48
22	6/02/2015	2048	158	13	0.71
23	8/02/2015	1925	192	10	0.67

Figure 3 presents the measured electrical power used by the compressors, fans and pumps over a testing period. The figures highlight how the compressors were online during the off peak period from 8 pm to the following midday and offline during the 8 hour daytime peak period, with a nominal peak demand of 120 kW. Figure 3 shows how 8 hours of discharge was achieved consecutively for 11 days. It also shows that fan power is relatively constant, with a maximum power of 40 kW. The pumping power for the heat transfer fluid (HTF) shows the cycle of charging and discharging. During charging the pumping power is around 30 to 40 kW whereas during discharge the pumping power is approximately 10 kW. Therefore the majority of pumping power is attributable to the evaporator. Overall the data suggests that pumping power associated with the PCM tanks is small.

Figure 4 presents the thermal power throughout the system for the 17th and 18th January, when full charging of the PCM was achieved. Each heat flow was calculated based on the temperature difference and flow rate through the component. During midnight to 6:00 am, the refrigeration plant is freezing only the PCM. During this period the evaporator load is relatively constant at around 280 kW. After 6 am the rooms are engaged and the refrigeration plant is cooling the rooms and freezing the PCM simultaneously. During this period between 50 to 100 kW is used to freeze the PCM and the remaining thermal power to cool the rooms. Between 12:00 noon to 20:00, the compressor is turned off and only the PCM is used to provide the cooling. Here the PCM thermal power matches the room load.

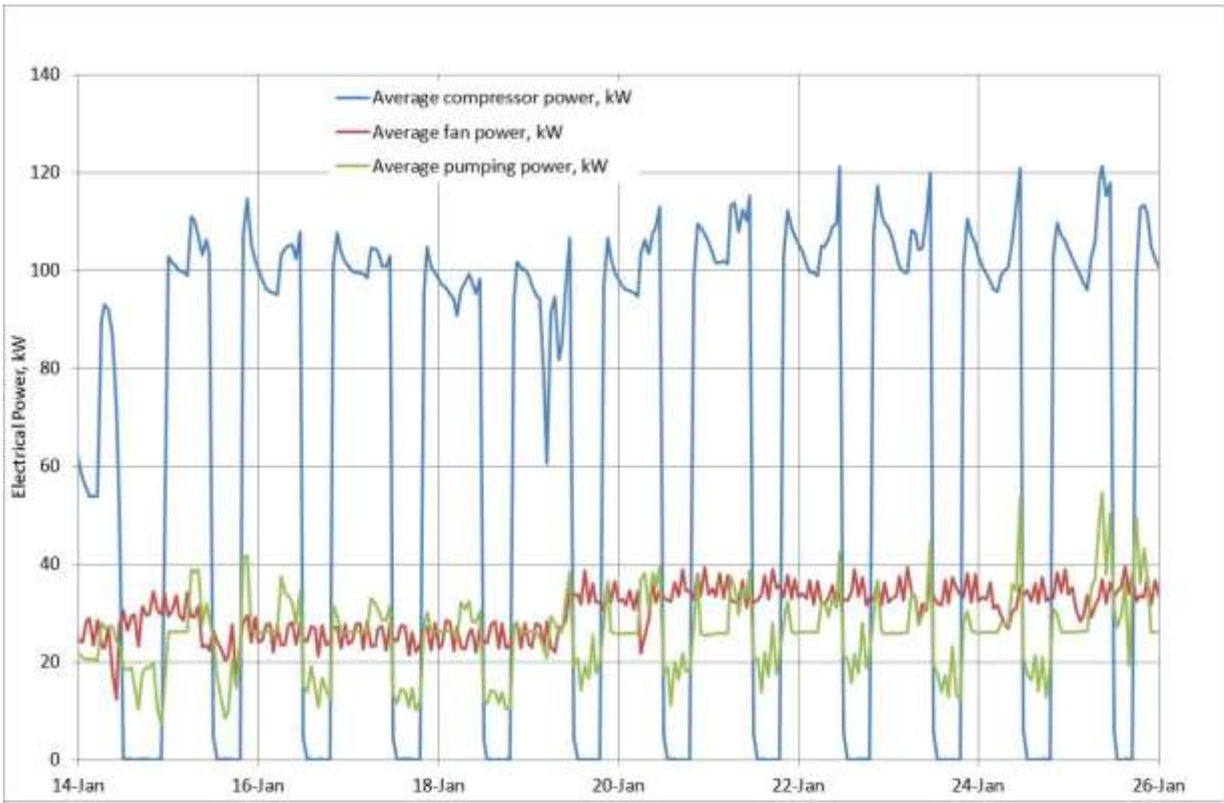

Figure 3. Electrical power profile of refrigeration system during operation in January 2015.

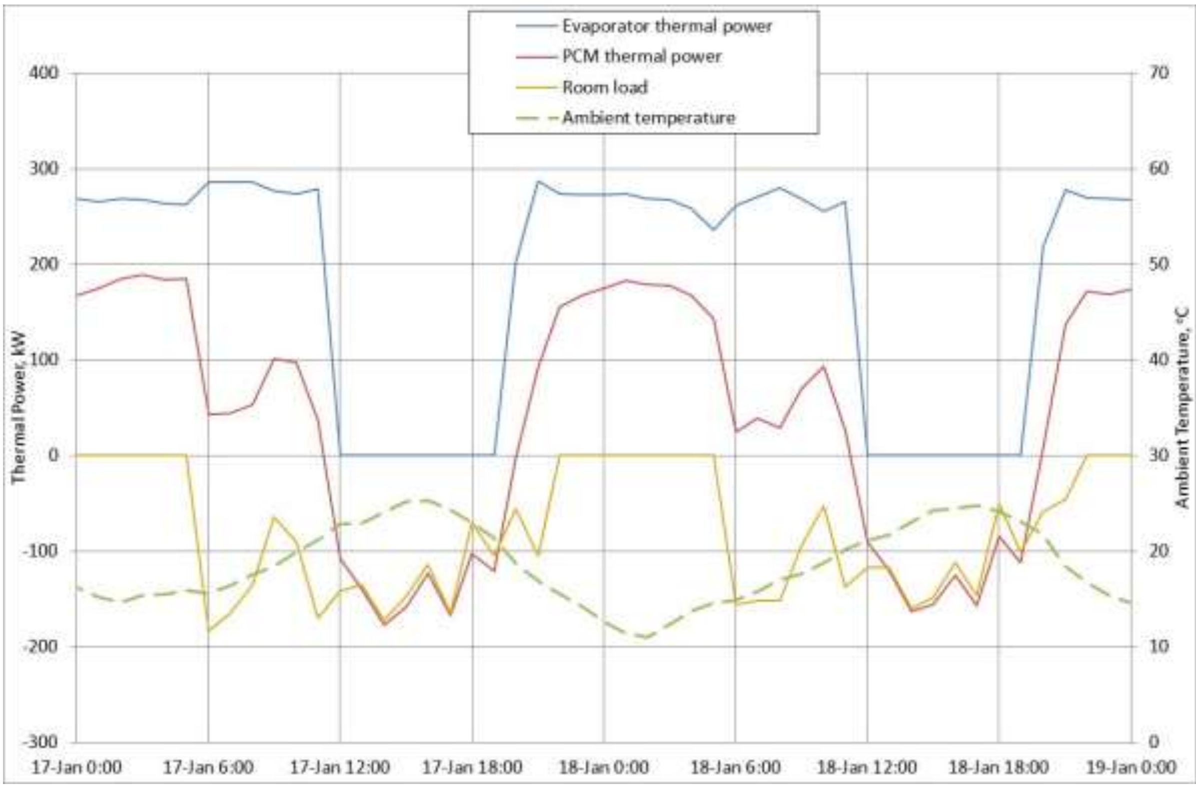

Figure 4. Thermal power profile of PCM and refrigeration system 17-18th February 2015.

4. Performance of Thermal Storage

Independent of the refrigeration system, the performance of the thermal storage system was evaluated in relation to its capacity to consistently store thermal energy. Figure 5 presents the average of all tank temperatures together with the inlet and outlet temperature of the HTF for the 17th and 18th January. On the 17th January, between midnight and 12:00 noon, the average temperature in the PCM tank was equivalent to the freezing point of the PCM (-11°C). After 12:00 noon, when the PCM only was being used to cool the rooms, the PCM temperature increased to -8 degrees C, demonstrating that some of the PCM melted. On the 18th January, during freezing the PCM between midnight and noon, the temperature of the PCM went below -13°C. This meant that the PCM was completely frozen and the thermal storage facility fully charged.

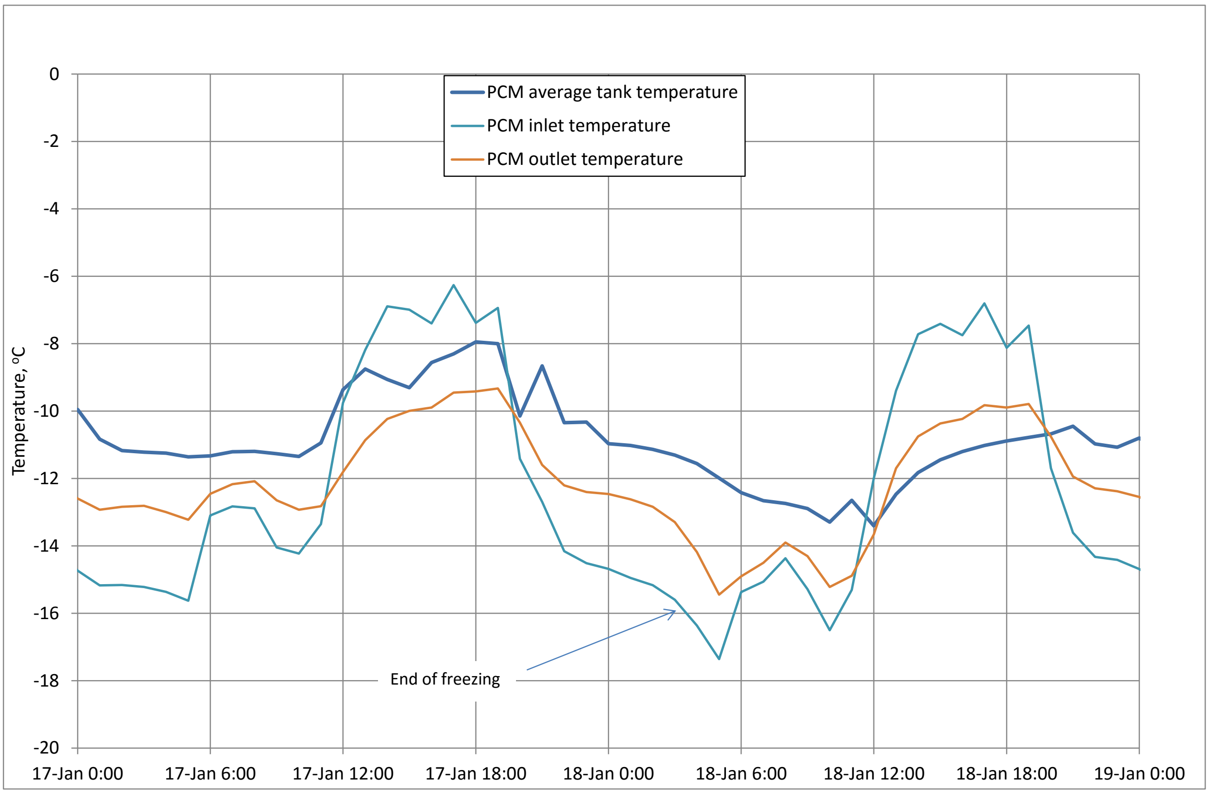

Figure 5. Temperature profile during charging/discharging cycle 18 January 2015, showing complete charging.

A critical performance requirement of the thermal storage system is the long term reliability of the PCM. Table 3 shows the latent energy of samples taken from the PCM tanks over 2014. Although the PCM was not fully charged every day, the repeated cycling subjected the PCM to a large number of melt/freeze cycles. Table 3 shows no measureable degradation.

Table 3. Latent energy test results of PCM samples.

Sample	Baseline	1	2	3	4	5
Latent heat of fusion (kJ/kg)	296	282	278	294	294	281
Percentage Difference (%)	-	4.7	6.0	0.5	0.5	5.1

5. Conclusions

A PCM thermal storage system incorporated with an ammonia refrigeration system has been designed, constructed and tested on a commercial scale. The capability of the PCM thermal storage system to charge and discharge near its rated capacity was demonstrated. Furthermore, no degradation in thermal capacity was observed over the testing period.

The refrigeration system together with the storage facility successfully achieved a peak demand reduction during the summer period. The system was able to shift the electricity load from the peak to off-peak electricity period using PCM. In addition, testing after one year has shown that the PCM has not degraded. It has been successfully demonstrated that a PCM thermal storage system can be used to shift the electricity load for cold storage from peak to off-peak periods.

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