Performance Studies of Refrigerated Van having PCM for Generating Off Site Refrigeration Effect

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A refrigeration system incorporating phase change material (PCM) is proposed to maintain refrigerated van at the desired thermal conditions. The advantage of using PCM to maintain low temperatures is that a conventional refrigeration system does not have to be located on-board the vehicle. In addition, Thermal Energy Storage through Phase Change material has been used for wide applications in the field of air conditioning and refrigeration especially at industrial scale. The specific use of this Thermal Storage has been for Energy Storage during low demand and release of this Energy during peak loads with potential to provide energy savings due to this. The system consumes less energy and produces much lower local greenhouse gas (GHG) emissions. The phase change material is charged by a refrigeration unit located off the vehicle when stationary. The PCM is discharged and provides cooling when in service. A new PCM with a lower cost than currently available PCMs was developed, suitable for maintaining the refrigerated van at a temperature of 5°C. The PCM has a melting temperature of -15.2°C and a latent heat of 284 kJ/ kg. The use of latent heat storage is especially suited to the storage of energy to prolong the food preservation time of refrigerators fresh food compartment & also improve the cooling cycle by its release at appropriate time. A prototype system was constructed and test results proved that the proposed refrigeration system is feasible for mobile transport.

Keywords: Phase change material (PCM), Thermal energy storage, Greenhouse gas (GHG).

1. INTRODUCTION

Food transport refrigeration is a critical link in the food chain not only in terms of maintaining the temperature integrity of the transported products but also its impact on energy consumption and CO_2 emissions. Refrigerated transport is necessary for maintaining the quality and prolonging the shelf-life of fresh, frozen and perishable products during transportation. The product temperature needs to be kept at the point where metabolic and microbial deterioration is minimized. The population growth and the consumer's continuous demand for fresh food have contributed to an increasing demand for refrigerated transport. Refrigerated transport is of significance because it connects the various stages between the initial production and the consumer. On average, foodstuff is transported 2.5 times or more over a distance of 2100 km before arriving on the consumer's plate [1]. The journey length, energy use and greenhouse gas (GHG) emissions associated with food transport has received considerable attention recently. In US, over 75% of food is produced, packaged, shipped and stored under certain levels of refrigeration. By 2002, the estimated number of refrigerated trucks in use was around 1.2 million worldwide [2]. The cost of the worldwide transported goods was approximately 1200 billion US dollars [3].

Refrigeration systems are essential for maintaining the temperature in the refrigerated space at the required level. At present, the predominant technology in refrigerated road transport is mechanical vapor compression refrigeration driven by a diesel engine. This type of engine is relatively expensive, noisy and its efficiency is only 35–40% [4]. The poor performance of the on-board refrigeration unit is due to the requirement of light components (compressor, condenser and evaporator) and the limitation of space to fit these components [5]. Consequently, the evaporator is close to the condenser and the diesel engine.

Another drawback of the diesel engine driven refrigeration system currently in use is the associated GHG and particulate matter emission. They are harmful to people's health and contribute to global warming. On average, a typical refrigerated vehicle will produce approximately 50 tons of CO_2 annually with a fuel consumption of 0.47 L/h per kW cooling capacity, operating at an outside temperature of 30^{o}C and refrigerated space temperature of -20 ^{o}C [6]. Furthermore, the amount of CO_2 emission from a typical system is expected to increase at a rate of about 5% annually because of the aging of the insulation in the vehicle.

In the present work, a novel refrigeration system for a refrigerated van is proposed. The refrigeration system consists of an on vehicle phase change storage unit, an off-vehicle refrigeration unit. The refrigerated space is required to be maintained at a temperature of 5 ^{0}C. Generally, Vegetable and fruits are required to be delivered at 5 ^{0}C to minimize quality loss during transportation [6].

In this study, a new PCM was used with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing or releasing large amounts of energy per unit mass. Mehling and Cabeza [7] give detailed illustrations about the PCM's classification, characteristics, limitations, measurement techniques and applications. To our knowledge, the work presented in this paper is innovative in two aspects. Firstly, a low-cost PCM that can store and release cooling energy at -15.2 ^{0}C is used and secondly, it is the first time that a PCM is incorporated into the refrigeration system on refrigerated van with the charging being done by a refrigeration unit off the vehicle.

Vehicle is stationary in the warehouse or depot. The refrigeration unit is powered by electricity instead of an internal combustion engine and it is located in the warehouse instead of on the vehicle. In comparison to the conventional system, the proposed system is expected to have a lower noise level, reduced energy cost and much lower local GHG emission. Also, the maintenance for the new refrigeration system is low compared to the conventional system because many moving parts of the refrigeration system are eliminated. In stationary operation, the electrically driven refrigeration units are highly efficient, extremely quiet and highly reliable [8]. Therefore, the performance and thermal efficiency of the refrigeration unit will be improved. In addition, once recharged, the new refrigeration system on the vehicle is likely to be more reliable and will prevent sudden temperature changes and consequently result in higher quality food because of the buffer effect of PCM.

2. EXPERIMENTAL SET-UP

2.1. Refrigerating Van

The experimental set-up consists of a efrigerating Van (165 L) as shown in Figure1 to Figure 4. The characteristics of the van used are presented in Table 1.

Table 1:. Characteristics of the experimental refrigerating Van (165 L).

Characteristics	Units	Value
Width	cm	45
Depth	cm	45
High	cm	89
Capacity	L	165
Working temperatures	ºC	5

Fig. 1: Frontal view of the statical van used in this study.

Fig. 2: Statical van with sensor.

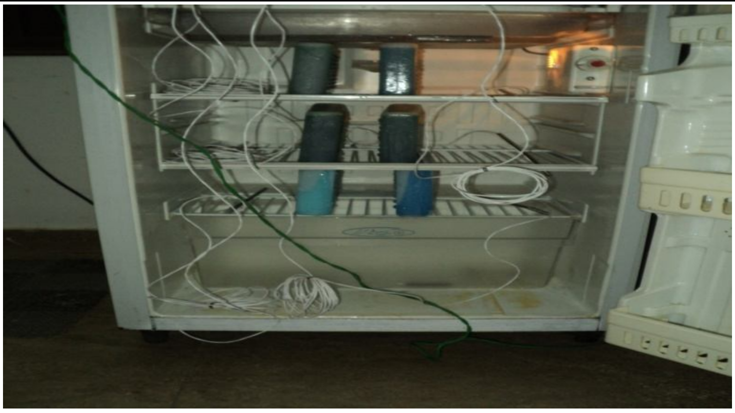

Fig. 3: Statical van PCM with sensor.

Fig. 4: Statical van with PCM, sensor and fan.

A Refrigerating van was used for testing of the performance of PCM in a van. Under this type of system, placing the PCM was in different combination.

2.2. PCM

The basic form of the PCM without any additives was used for this investigation. The physical data of the PCM are presented in Table 2.

Table 2: Physical data of the PCM.

Characteristics	Units	Value
Phase change temperature	ºC	-15.2
High Latent heat of fusion	kJ/ kg	284
Approx. specific heat in PCM	kJ/ kg K	231
Density (liquid)	Kg/ m^3	1013
Thermal conductivity	W/ m ºC	0.5-0.7

The total volume of each PCM was 0.0013 m^3 (260 x 125 x 40 mm each begs) and mass of each cool pad is 0.9 kg.

2.3. Measurement Devices

Thermocouples (Pt-100) resistance and temperature detector (RTD) were used for temperature measurements at different locations inside the Refrigerator van, and all the thermocouples were calibrated. These thermocouples are suitable for use in the temperature range of -150 C to +100 C and giving very accurate measurements (< 0.1° error). Thin wire thermocouples were used so that when placed into the van, the leads would have a minimal effect to the Refrigerator van door seals that prevent moisture from entering the Refrigerator. Six air temperature sensors were located inside the Refrigerator van as shown in Figure 2. Air temperature was measured using Pt-100 DIN Class B thermocouple inserted into a 4 mm diameter steel cylinder having a length of 30 mm.

2.4. Experimental Plan

The PCM can be charged by a refrigeration unit when the vehicle is stationary in the warehouse or depot. The refrigeration unit is powered by electricity instead of an internal combustion engine and it is located in the warehouse instead of on the vehicle. During the freezing process, the PCM solidifies and the cooling energy is stored. The PCM can discharge the stored cooling capacity when it is on the road. During the discharging process, the PCM when melting will release the cooling energy to exchange heat with air in the cooling unit.

In comparison to the conventional system, the proposed system is expected to have a lower noise level, reduced energy cost and much lower local CO_2 emission. Also, the maintenance for the new refrigeration system is low compared to the conventional system because many moving parts of the refrigeration system are eliminated. In stationary operation, the electrically driven refrigeration units are highly efficient, extremely quiet and highly reliable. Therefore, the performance and thermal efficiency of the refrigeration unit will be improved. In addition, once recharged, the new refrigeration system on the vehicle is likely to be more reliable and will prevent sudden temperature changes and consequently result in higher quality food because of the buffer effect of PCM. The proposed refrigeration system is suitable for both small and large refrigerated van and for relatively short and local delivery use. However, this refrigeration system cannot provide heating in severe winter conditions.

Using this Refrigerator set-up, a number of experiments were conducted to investigate the performance of PCM inside the Refrigerator van with PCM in static condition and dynamic state. Also investigate the performance of PCM inside the Refrigerator van with varying the surface area (mass) in both static and dynamic conditions. The purpose of these experiments was to study the temperature response of the air inside the van. Table 3 lists the sets of experiments conducted in van.

Table 3: Details of the different PCM used in this study.

Numbers of PCM	Mass of PCM (kg)	Surface area of PCM (m^2)	With fan	With fan and fin
3 PCM	2.7	0.19	no	no
4 PCM	3.6	0.36	no	no
6 PCM	5.4	0.51	no	no
6 PCM	5.4	0.51	yes	no
6 PCM	5.4	0.51	yes	yes

3. RESULTS AND DISCUSSION

3.1. Response to Air Temperature with increase in Mass of PCM

In the first investigation, the performance of the Refrigerating van to increase the mass of PCM without fan and fin was conducted. Plastic bags, each containing 0.9 kg of PCM were prepared. The bags were placed in the refrigerating van. Location of temperature sensor and PCM are shown in Figure 3. The temperatures of the refrigerating van with PCM were recorded and tabulated in Table 4. Initially, the PCM was completely frozen and the temperature was maintained at around -2^{o}C. The ambient temperature during the test was approximately 30^{o}C.

Table 4: Comparison of temperature of varying mass of PCM.

Time (hours)	3 PCM, Average Temperature (°C)	4 PCM Average Temperature (°C)	5 PCM Average Temperature (°C)	6 PCM Average Temperature (°C)
0	-1.6	-1.5	-1.8	-1.55
0.15	-1.1	-0.96	-1.3	-1.41
0.30	-0.4	-0.01	-0.31	-0.91
0.45	0.45	0.98	-0.3	-0.56
1.00	1.5	1.68	0.23	-0.21
1.15	2.4	2.21	0.73	0.13
1.30	3.26	2.68	0.93	0.48
1.45	4.06	3.18	1.38	0.81
2.00	4.71	3.65	1.83	1.18
2.15	5.5	4.21	2.28	1.68
2.30	6.51	4.8	2.76	2.03
2.45	7.68	5.41	3.15	2.38

Time (hours)	3 PCM, Average Temperature (°C)	4 PCM Average Temperature (°C)	5 PCM Average Temperature (°C)	6 PCM Average Temperature (°C)
3.00	8.91	5.98	3.63	2.68
3.15	10.01	6.43	4.13	3.03
3.30	11.13	7.23	4.56	3.38
3.45	12.28	8.13	5.05	3.73
4.00	13.16	9.35	5.53	4
4.15		10.18	5.96	4.4
4.30		11.46	6.45	4.7
4.45		12.56	6.93	5
5.00		13.96	7.46	5.41
5.15			7.98	5.71
5.30			8.58	6.21
5.45			9.01	6.61
6.00			9.58	6.98
6.15			10	7.33
6.30			10.53	7.68
6.45			11	8
7.00			11.18	8.53
7.15			12	8.88
7.30				9.28
7.45				9.71
8.00				10.11
8.15				10.61
8.30				11
8.45				11.45
9.00				11.93

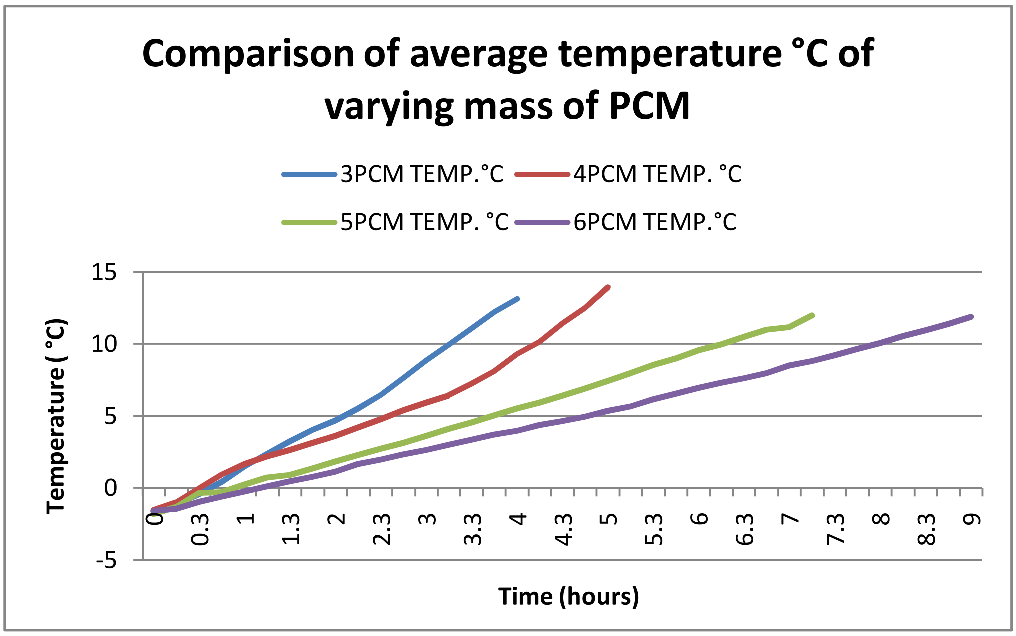

Fig. 5: Comparison of temperature of varying mass of PCM.

The refrigerator was gradually cooled down to 5°C at around 2.15 hours (3 PCM), 2.45 hours (4 PCM), 3.45 hours (5 PCM) and 5 hours (6 PCM). Results of this experiment are summarized in Table 5 and Figure 5 under first investigation.

Table 5: Results of investigation on air temperature with mass of PCM.

Mass of PCM (Kg)	Temperature starting the experiment (°C)	Temperature maintain inside the refrigerator (°C)	Time (hours)
2.7	-1.5 °C	5 °C	2.15
3.6	-1.5 °C	5 °C	2.45
4.5	-1.5 °C	5 °C	3.45
5.4	-1.5 °C	5 °C	5

3.2. Response to Air Temperature with PCM with Fan and PCM with Fan and Fin

In this second investigation, two performances of the Refrigerating van were observed. First experiment was conducted by 6 PCM with fan and second experiment was conducted by 6 PCM with fan and fin. Plastic bags, each containing 0.9 kg of PCM were prepared. The bags were placed in the refrigerating van. A fan positioned at the bottom of the freezer provided air circulation into the refrigerator compartment. In second experiment the PCM were placed with aluminum fin a fan positioned at the bottom of the refrigerator provided air circulation into the refrigerator compartment. Location of temperature sensor with PCM with fan and fin are shown in Figure 4. The temperatures of the refrigerator with PCM were recorded and tabulated in Table 6. Initially, the PCM was completely frozen and the temperature was maintained at around -2^{o}C. The ambient temperature during the test was approximately 30 ^{0}C.

Table 6: Comparison of air temperature variation with 6 PCM, 6 PCM with fan and 6 PCM with fan and fin.

Time (hours)	6 PCM, Average Temperature (°C)	(6 PCM + fan), Average Temperature (°C)	(6 PCM + fan + fin), Average Temperature (°C)
0	-1.55	-1.85	-1.93
0.15	-1.41	-1.45	-1.73
0.30	-0.91	-1.15	-1.53
0.45	-0.56	-0.85	-1.23
1.00	-0.21	-0.6	-0.98
1.15	0.13	-0.35	-0.73
1.30	0.48	-0.1	-0.43
1.45	0.81	0.2	-0.13
2.00	1.18	0.46	0.17
2.15	1.68	0.75	0.37
2.30	2.03	0.98	0.58
2.45	2.38	1.23	0.83
3.00	2.68	1.48	1.13
3.15	3.03	1.75	1.33
3.30	3.38	1.98	1.53
3.45	3.73	2.18	1.83
4.00	4	2.43	2.08
4.15	4.4	2.7	2.33
4.30	4.7	2.91	2.6
4.45	5	3.21	2.8
5.00	5.41	3.41	3.12
5.15	5.71	3.66	3.32
5.30	6.21	3.96	3.57
5.45	6.61	4.21	3.82
6.00	6.98	4.41	4.02
6.15	7.33	4.61	4.22

Time (hours)	6 PCM, Average Temperature (°C)	(6 PCM + fan), Average Temperature (°C)	(6 PCM + fan + fin), Average Temperature (°C)
6.30	7.68	4.8	4.42
6.45	8	5.03	4.62
7.00	8.53	5.33	4.82
7.15	8.88	5.73	5.02
7.30	9.28	5.98	5.27
7.45	9.71	6.23	5.4
8.00	10.11	6.53	5.82
8.15	10.61	6.93	6.12
8.30	11	7.23	6.32
8.45	11.45	7.51	6.57
9.00	11.93	7.76	6.8
9.15		8.16	7.1
9.30		8.46	7.35
9.45		8.86	7.55
10.00		9.16	7.85
10.15		9.58	8.1
10.30		9.88	8.25
10.45		10.28	8.55
11.00		10.78	8.8
11.15		11.28	9.05
11.30		11.68	9.35
11.45		12.1	9.62
12.00		12.43	10
12.15			10.3
12.30			10.6
12.45			10.9
13.00			11.1

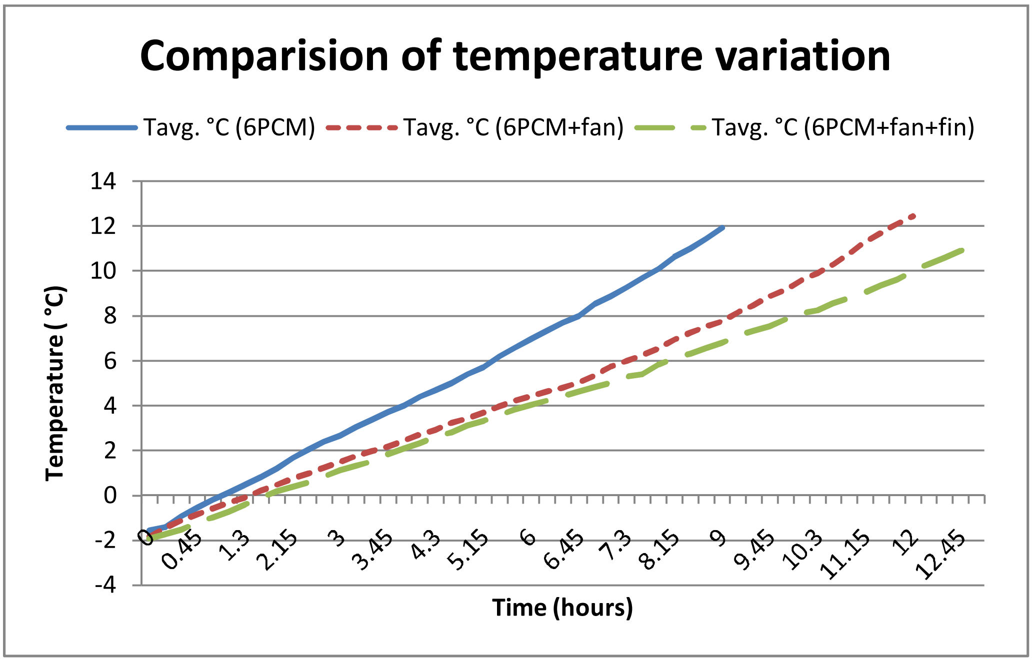

Fig. 6: Comparison of air temperature variation with 6 PCM, 6 PCM with fan and 6 PCM with fan and fin placed in van.

A comparison of the average air temperature inside the refrigerator with 6 PCM, 6 PCM with fan and 6 PCM with fan and fin can be seen in Figure 6. It is able to keep the temperature in the refrigerator at 5°C for 5 hours (6 PCM), 6.45 hours (6 PCM with fan) and 7.30 hours (6 PCM with fan and fin). The air temperature with 6 PCM, 6 PCM with fan and 6 PCM with fan and fin increases but at a slower rate when PCM with fan and fin is used. Results of this experiment are summarized in Table 7.

Table 7: Results of investigation on air temperature variation with 6 PCM, 6 PCM with fan and 6 PCM with fan and fin.

Experiment detail	Temperature starting the experiment (°C)	Temperature maintain inside the refrigerator (°C)	Time (hours)
6 PCM	-1.5 °C	5 °C	5
6 PCM with fan	-1.5 °C	5 °C	6.45
6 PCM with fan and fin	-1.5 °C	5 °C	7.30

4. CONCLUSION

In the present work, a novel refrigeration system with an off vehicle refrigeration unit and an on-vehicle latent heat thermal storage unit has been proposed for refrigerated van. In this paper, a new low cost PCM suitable for the refrigeration system was used. This paper has shown that use of PCM in the Refrigerating van can limit the rise in air temperature inside the cold storage facility during loss of electricity. As the PCM melts, it absorbs the thermal load that enters the cold storage space, thus limiting the rise in the cold store temperature. These results show that PCM could be utilized to limit temperature rises during loss of electrical power, which may occur due to an accidental power loss or done purposely to achieve electrical load shifting. This work extended to investigate the effects of increasing the mass, use of fan with fins. In addition, the refrigeration system produces much lower local GHG emissions and it has improved temperature control and reduced noise level. In future work, more characteristics of the PCM will be explored, such as the volume contraction of the phase change and the thermal stability.

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