Sustainable Techniques in Refrigerated Space

Sustainability and high performance of refrigerated space used for the preservation of perishable product capitalizes on conservation techniques which reduce environmental impact. The concept embraces a variety of techniques including the exchange, or supplementation of mechanical refrigeration systems by Thermal Energy Storage (TES) that incorporate Phase Change Materials (PCM), and advanced refrigeration control. By using TES as a part of an integrated system, overall efficiency can be improved resulting in lower energy costs.

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Introduction

The application of the TES system can improve the operating efficiency of the existing refrigeration equipment without costly replacement, while improving the shelf life and quality of perishable foods and other products:

1. Refrigeration equipment can operate longer at higher suction pressures and higher coil delta temperatures, where it is more efficient.
2. Refrigeration equipment can operate at lower condensing pressures, reducing compressor KW.
3. Reduction of refrigeration equipment total runtime required to condition the space, resulting in extended equipment life and a reduction in maintenance costs.
4. TES has the ability to shift load throughout the day by leveraging the thermal energy storage capacity of the TES to match the utility rate structure and operational needs of the electric utility with Demand Response and Smart Grid Integration capability.
5. Incorporation of intelligent defrost capability, reducing the energy impact of defrost.
6. Ability to respond dynamically to real world usage scenarios, including product loading and power outages.
7. Preemptive detection of need for service, including service pre-classification.
8. Effective management of moisture (relative humidity) in the room, to improve safety and equipment efficiency.
9. Improve quality of product through the reduction of product temperature fluctuation and open product shrinkage, while minimizing low temperature suction pressure (temperature) which extracts excessive moisture.
10. Refrigeration equipment sizing could target average load rather than peak load, leading to lower initial cost.

The following discussion relates to the operation and use of commercial refrigeration equipment for operating freezer and cooler perishable product storage space. The system employs the use of Thermal Energy Storage cells (TES) installed in the ceiling areas of refrigerated rooms combined with intelligent controls, and a 24/7 remote monitoring package.

Executive Summary

The U.S. refrigerated storage industry is estimated to consume $13B of electricity annually. Electrical cost represents one of the largest component of operating expense of a typical refrigerated facility. Deemed the most significant technological development in the last 100 years, refrigeration stands paramount to our quality of life and fundamental to the needs of perishable food logistics. The refrigerated storage industry has expanded by 22% over the past 10 years. Because of this, the industry has placed an emphasis on energy saving technologies.

Thermal Energy Storage (TES) represent a key component of an effective energy reduction strategy in refrigerated space. By utilizing TES as a part of a dynamic system incorporating advanced control of refrigeration equipment, various strategies can be employed to achieve operating cost reductions for a refrigerated facility.

TES represent a stand-alone, minimum maintenance addition to the refrigerated system with an effective lifetime that can exceed that of the mechanical equipment. The system as a whole can enable electrical energy savings that affect both the demand and consumption components, and can enable a facility to leverage utility rate programs and discounts offered by electrical utility providers.

Introduction

The Latent Energy Cycle

To properly understand the way TES can be used in a refrigerated environment, it is important to understand the difference between sensible and latent heat. When thermal energy is transferred into or out of a perishable product, that product becomes measurably warmer or colder. This is called sensible heat, and can be measured using conventional temperature measurement devices. Latent heat in this case occurs when a material is going through a phase change from solid to liquid and that material is capable of absorbing thermal energy without becoming measurably warmer or colder for the duration of the phase change process. Once the phase change is complete, the product heat becomes sensible (and measurable) again.

The primary benefit of utilizing TES implemented with Phase Change Materials (PCM) in a refrigerated environment is the ability of PCM to efficiently store thermal energy while in latent mode. As thermal heat enters the refrigerated space through infiltration, refrigeration equipment, lighting, people, forklifts, etc., this thermal heat can be captured in modules holding PCM, rather than in the product being stored in the facility. This happens because the PCM is efficient at capturing thermal energy while the PCM is undergoing a state change from solid to liquid, and collectively the PCM has a large thermal capacity compared to sensible heat. The PCM can store 100 times more thermal energy in latent mode than a one degree sensible heat change in stored product. Figure 1 is a chart illustrating sensible and latent heat during the phase change process.

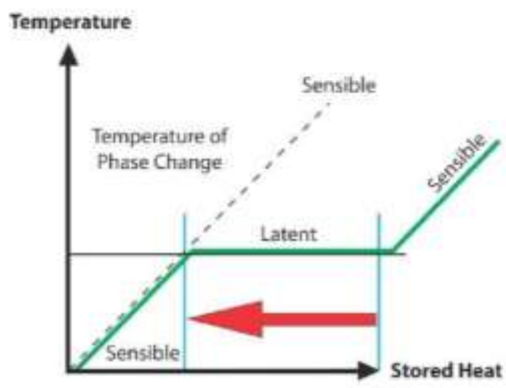

Figure 1 Latent and Sensible Heat vs. Temperature

TES modules containing PCM are placed above the storage racking shown in Figure 2 so that they are above the product and are also placed inside the air stream of the evaporator fans. This allows heat to flow via convection to the TES when the air units are off. Once the TES reach their thermal capacity absorbing heat, the air flow from the evaporator fans can efficiently and directly cool the cells back to the solid state.

Figure 2: Example installation

The phase change materials in the TES system provide latent heat capacity to the refrigerated environment, allowing the TES to absorb a large amount of thermal energy from the surrounding environment while remaining at the same temperature. This functions to allow the refrigerated environment to maintain a cold operating temperature for an extended time period without running the mechanical system(s). The freezer TES systems operate on a continuous 24-hour cycle. The latent heat capacity of the system reduces the frequency of compressor cycling by providing a larger heat sink on which the compressor can now work on while operating at a higher, more efficient, suction pressure.

Effects on Operating Efficiency

By employing TES in a refrigerated space, measurable improvements in equipment and system efficiency can be realized. By managing the existing refrigeration equipment to leverage the thermal capacitance of the TES, existing refrigeration equipment is able to operate at peak design efficiency, often exceeding typical performance. This effectively improves the coefficient of performance of the equipment, EER of the compressor and the SEER of the system.

Higher Suction Pressure

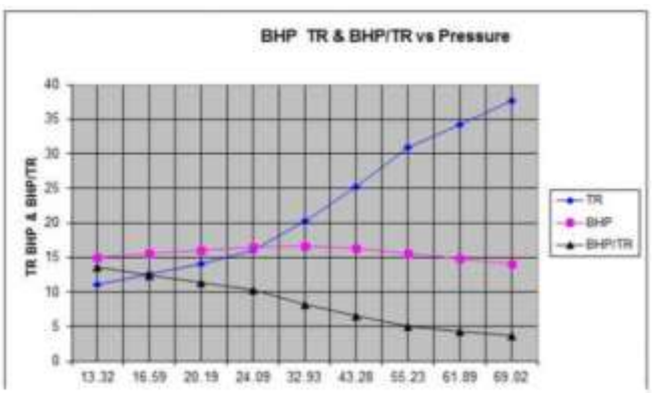

Figure 3 BHP/TR vs. Pressure

Compressors for refrigeration systems are designed for peak conditions. Operation is typically at partial load conditions for the majority of the life of the compressor. By imposing an additional load (TES) on the system, the compressor will operate at higher suctions and improved horsepower/ton, EER and SEER.

Figure 3 shows the relationship of BHP/TR as pressure goes up and down. These are actual ratings of industrial large bore and stroke reciprocating compressors pumping R-22. This shows a 2.7% improvement in BHP/TR for a 1 degree rise in suction temperature. In small bore hermetic compressors this is more dramatic due to the small bore and higher operating speeds. By increasing the run time at higher suction temperatures the net or SEER efficiency is improved significantly.

As air unit coils lose their load, the ΔT becomes small, the liquid flow is shutoff by the expansion valve, so the long circuits boil off the liquid refrigerant and the rest of the circuit superheats the gas returning to the compressor. This is one of the built in inefficiencies of DX systems because expansion valves are designed to operate as a function of superheat. Unlike industrial coils, a recirculated system where liquid is over fed to maximize coil heat transfer, DX coils leave about 30% of the coils surface to make sure the DX valve can provide superheat with which to regulate its DX valve.

The superheat is a menace for several reasons. It forces the compressor to operate less efficiently by pumping superheated gas instead of saturated gas, and it tends to wire draw the parts inside the DX valves. The compressor itself suffers because it now operates at higher outlet temperatures, higher compression ratios and with less efficiency. More blow-by is experienced which causes wear, breakdown of oil, etc. By forcing the compressor to operate at higher and more efficient suction conditions, the system operates at a lower horsepower per ton (better coefficient of performance, EER, SEER, etc.).

Horsepower/ton at normal operations will vary from .55 to .502 as the compressor cycles throughout the day and night, as well as weekends. By imposing a greater load, the horsepower is optimized somewhere between .47 and .43. In addition, fan cycle time reduces the horsepower/ton in proportion to additional off cycle time. Typically, this shows a 30% reduction in net power consumption while maintaining the same product temperatures as before TES was installed.

Pres	TR	BHP	10 X BHP/TR	TEMP	EER
13.32	11	15	1.364	-15	6.56
16.59	12.5	15.5	1.240	-10	7.22
20.19	14	16	1.143	-5	7.83
24.09	16	16.4	1.025	0	8.73
32.93	20.2	16.6	.822	10	10.89
43.28	25.2	16.3	.647	20	13.83
55.23	30.9	15.5	.502	30	17.84
61.89	34.2	14.8	.433	35	20.68
69.02	37.7	14.1	.374	40	23.92

Table 1 HP/TR vs. Pressure for industrial compressor at 106.2 PSIG Discharge Pressure

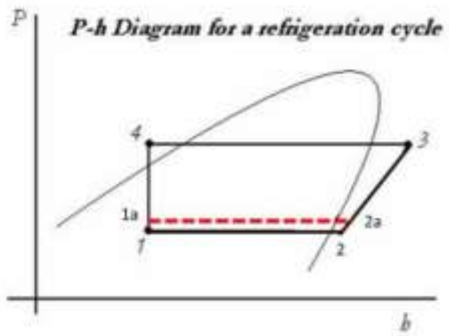

Figure 4 Pressure vs. Enthalpy

All compressors have operating curves for capacity and KW (horsepower) relationships. While this may vary from compressor type (reciprocal or scroll), the relationship is much the same. For cooler conditions, as the pressure is raised, compressor capacity will go up and the KW (demand) will go up, however, the ratio KW/TR will improve as it is going up.

For Freon a typical relation is for 1 degree increase in suction temperature, the kw/TR will improve by 2%. In reviews of the actual graph of an operating system, and the run time during the "chill down" cycle which with the TES is 4 to 5 times longer than without them, one can see that the compressor(s) ran approximately 30% longer at elevated conditions (warmer) while chilling the TES Graphically, as shown in Figure 4 raising the suction pressure increases the bottom line of the P-h diagram from 1-2 to 1a-2a, reducing the power consumption for the system.

Lower Condensing Pressure

Refrigeration equipment can operate more efficiently at lower condensing pressures. This is evident by looking at NOAA weather charts where typical temperatures will be 10 °F to 20 °F cooler during the night. The ambient temperature determines the pressure. A rule of thumb is for each 5 PSI drop in discharge pressure, motor amps drop 2% and capacity goes up 1%. A 10 °F drop in air temperature can be a 4% gain in efficiency (COP/EER or SEER) by shifting the load to night time. Where utilities have off peak rates, the savings will be more pronounced. The following Table 2 shows the saturated relationship of discharge pressure to temperature.

Temp F	Pressure	
	psia	psig
82	164.5	149.8
84	169.4	154.7
86	174.5	159.8
88	179.6	164.9
90	184.8	170.1
92	190.1	175.4
94	195.6	180.9
96	201.2	186.5
98	206.8	192.1
100	212.6	197.9
102	218.5	203.8
104	224.6	209.9
106	230.7	216
108	237	222.3
110	243.4	228.7
112	249.9	235.2
114	256.6	241.9
116	263.4	248.7

Table 2 Relation of Pressure and Temperature at Saturated Condition

Increased Coil Efficiency

Efficiency is also improved by operating the coil surface of the evaporators at higher temperature differences (ΔT). The effective ΔT of the refrigerated
space evaporator is raised; the TES system no longer lets the coils go into a low suction ΔT mode. The system forces the coil to operate at more optimum conditions by making it operate at a higher ΔT, making both the product and the TES a cold heat sink. In effect, this transfers more heat in less time, resulting in a net lower compressor and fan runtime (reduced kWh). This enables the system to emulate original peak design conditions.

Reduced Runtime and Capacity

The increased thermal capacity offered by TES can allow for refrigeration equipment sizing to be skewed towards average load rather than peak load, because the additional thermal mass allows the room to warm more slowly, and the TES absorbs heat more efficiently than stored product both in rate of transfer and in its heat capacity. Otherwise, the compressor would cycle repeatedly from high down to low pressure when at lower than peak load condition. This is necessary the keep product temperatures within their range. TES prevents the short cycling and permits the compressor to operate for longer periods then turn off for extended periods while the TES cool the room. Repeated cycling is mechanically detrimental to the fans and compressors. Compressor run times have been effectively reduced by as much as 50%, using the TES system.

Also, TES can mitigate the need for backup refrigeration capacity in certain situations. This can lead to a reduction of refrigeration equipment capacity and runtime required to condition the space, resulting in lower up-front expense, extended equipment life, and a reduction in maintenance costs.

Effective Envelope Improvement

By utilizing TES, the room envelope efficiency is effectively improved by limiting the impact of infiltration. Placing TES above product, near doorways, along ceilings, and other sources of infiltration, the impact of infiltration on stored product quality can be reduced as the TES will absorb infiltration more efficiently than the stored product.

Operational Strategies

Introduction of the TES into the controlled space allows for various strategies to be employed that shift demand over time. By combining this capability with efficient defrost strategies, the refrigerated system is more efficient while being more responsive to real world conditions.

Efficient Refrigeration Cycle

A proprietary control algorithm operates a continual refrigeration cycle that optimizes equipment efficiency through integration of the TES with all phases of refrigeration control. This cycle leverages the latent energy capacity of the TES and integrates advanced defrost control strategy, while operating refrigeration equipment at peak efficiency as much as possible. The cycle is optimized for electrical consumption and demand savings, and can be tailored to match operational requirements.

Demand Shift and Demand Response

The additional thermal mass with latent heat storage capacity can extend the time between compressor cooling cycles. The thermal capacity is such that compressor off cycles can last for hours before the room and the TES need to be cooled again, while maintaining product integrity.

Figure 5 shows an actual product temperature rise of approximately 3 1/2 F degrees over an eight-hour period.

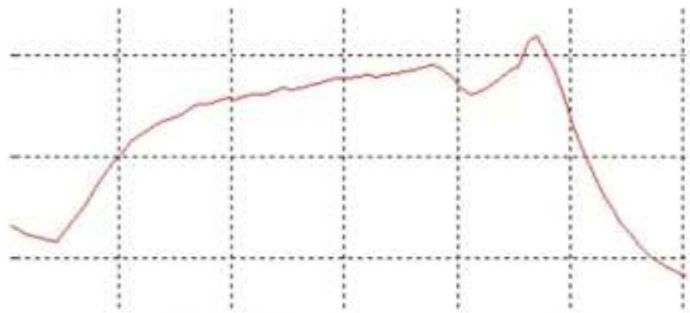

Figure 5 Room Temperature rise of 3.5F over 8 Hour Period

This ability to shift demand allows the controlled space to be operated within the framework of utility defined rate plan advantages, shifting electrical load from On-Peak to Off-Peak time windows. Each controlled space can also respond dynamically to conditions at a facility level, allowing the refrigerated space to be a part of a larger load shedding strategy initiated by a facility Energy Management System or by direct Smart Grid integration with the utility provider network. Multiple controlled spaces can be coordinated centrally to achieve the most efficient operation.

Demand-Response methodology calculations are fairly straightforward. It is the total BTUs consumed in an average day, as is shown in the following calculation. A sample calculation of the refrigeration load would include the following:

BTUs/day = Transmission + Infiltration + Equipment Heat+ Product

Intelligent Defrost

Coolers with temperatures at or near 35°F require defrosting to melt the ice formation during operation. Less ice and moisture is extracted with the TES system because the coil has been forced to operate more time at higher temperatures. While system designs vary, those with greater coil surface can operate at higher temperatures.

Traditional defrost cycles:

- 45-60 minutes per defrost, 3-4 defrosts per day.
- Surface temperature of heating element over 250F degrees for duration. Coil can reach 100F.

- Results in steam blown into space which will condense and freeze as frost on any surface.

TES defrost cycles:

- 20-25 minutes per defrost, only as needed; in freezers 1-2 defrosts per day, some coolers much less frequent (once per week)
- Temperature terminated defrost
- Demand defrost based on coil efficiency
- Heaters not operated for entire duration of defrost
- Observation of a proper drip-down time to let the coils dry before initiating fans

By optimizing cooling heat transfer temperatures in both the TES and in the evaporator, the infiltration air load is shifted and less moisture extracted. By managing the defrost process, less moisture from the evaporator coils blown back into the room after defrost.

Fewer defrost cycles lead to more uniform product temperatures, leading to less product shrinkage in open, unwrapped product.

Dynamic System

A refrigerated storage environment changes over time. The amount and type of product can change, as well as daily operations. By employing a cohesive control strategy involving the use of TES, the refrigerated system can adjust to both daily and general use fluctuations while protecting stored product and improving energy efficiency. The system can dynamically adjust control strategy to reflect real world conditions.

For example, if a controlled space is in a shifted demand period, but enough heat is introduced into the room via infiltration that product integrity is threatened, the system will take steps to protect the stored product even if that means a slight increase in energy consumption. This can be accomplished while maintaining a desirable demand profile. By measuring product temperature directly, the control system can leverage the thermal capacity of the TES while adequately protecting stored product.

Changes to the room envelope, such as door openings, are incorporated so that pending defrost cycles can be initiated at an advantageous time. For example, the room can be allowed to recover from an extended door opening before a defrost cycle is initiated that could further increase temperature.

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Other Benefits

There are several operational benefits to an integrated system with the controlled use of TES. The system has many of the capabilities of a traditional Energy Management System, including reporting, programmability, system integration, and operator interface options.

Because the system is actively monitoring equipment status through feedback sensors, automated messaging and alarming can be used to proactively detect the need for service and notify appropriate personnel. As the system often can determine the likely nature of the problem, service issues can be preclassified, limiting the potential scope of a typical service call.

Because the system can accurately monitor the state of stored product through repeated refrigeration cycles, the quality of stored product can be ensured. Reporting capability can offer facility operators the ability to produce product safety reports required by various government and industry agencies.

Summary

While there are other energy management systems in use, the Viking Cold system focuses on the product temperature, and with the use of TES, can provide energy reduction options not available with other systems. The Viking Cold solution improves the system efficiency (SEER) by operating the compressor at higher efficiency (EER) and permits other system components such as fans and compressors to cycle off more often. The use of TES also allows for significant load shifting and demand control capability not present with other solutions. By optimizing cooling heat transfer temperatures in both the TES and in the evaporator, and the addition of thermal mass, the impact of infiltration is also reduced.

Above there has been much discussion of the hidden heat of phase transformation known as latent heat when a liquid changes to solid, but the phase change of gas (water vapor) to liquid is far more dramatic. This phase change is significant because 1000 BTU/lb. is required to extract moisture from the air, and only 144 BTU/lb. is required to freeze water (TES is closer to water in energy terms). The TES absorb energy from air infiltration, reducing the amount of work the mechanical equipment must do directly. The reduction in infiltration refrigeration load is a significant part of the 30% plus reduction observed in the total space energy consumption.

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Appendix A – Technical Background

Phase Change Material (PCM)

A phase-change material (PCM) is a substance with a high latent heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy.

The latent heat of fusion, also known as enthalpy of fusion, is the amount of heat required to change a substance from a solid to a liquid.

The latent heat of fusion for PCM can be 300 times higher than the sensible heat, the energy value required to change an equivalent mass by one degree.

Boundary Layer Thermal Resistance

Adjacent bodies have a boundary thermal resistance between them. Thermal resistance restricts the flow of heat from one body to another. *Figure 3* below illustrates the difference between the thermal resistance of a TES cell and that of typical frozen products in cartons.

Figure 3A – The total R Value for the Thermal Energy Storage Cell is only R1, the convective boundary layer resistance.

Figure 3B – The total R Value for typical frozen food product, where R1,R3, & R4 are convective boundary layer resistances, and R2 is the resistance of corrugated cardboard.

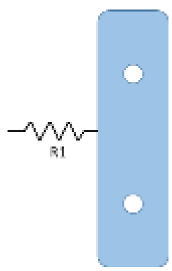

Figure 3A – TES Cell

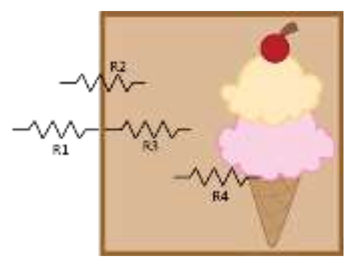

Figure 3B – Frozen Food in Packaging

When the refrigeration system operates, the evaporators are discharging air that is colder than the surroundings, creating the temperature differential required for heat to flow. Heat continuously flows seeking temperature equilibrium. The rate heat flows from one medium to another is a combined function of temperature differential and thermal resistance. The presence of both TES cells (low R value) and product (high R value) behaves like a parallel circuit, resulting in a greater proportion of heat flowing through the path of least resistance.