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ABSTRACT

The method and design of a novel Dual evaporator based domestic refrigerator with Phase Change materials (PCM) which provide thermal storage (TS) is presented .The usage of PCM as a TS will help to improve the COP (Co-efficient of performance) of new refrigeration cycle by introducing a new sub cooling routine. This improvement by sub cooling can be done for single evaporator refrigeration system or with even a dual evaporator system for a refrigerator / freezer combination. Because of prolonging of the compressor off time by using the latent heat of energy of the PCM we can have better food quality due to lower hysteresis cycles of on/off for a given period of operation .We have made system level modeling of the freezer / fresh food type domestic refrigerator and have also simulated the energy consumption using the new refrigeration cycle with sub cooling using PCM. Based on system design and modeling we have made experimental refrigerator prototype with new refrigeration cycle with PCM based TS and heat exchangers in the freezer and fresh food section. Test results and improvements in food quality are also presented. The energy efficiency results are also discussed.

1. INTRODUCTION

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. Lately though the application of this type of Phase Change materials for domestic refrigeration application to save energy or operate during the power outage has been under active consideration .The use of latent heat storage is especially suited to the storage of energy to prolong the food preservation time of domestic refrigerators fresh food compartment & also use the excessive stored energy can to improve the freezer cooling cycle by its release at appropriate time . The principle of latent heat storage using phase change materials (PCMs) can be incorporated into a thermal storage system suitable for use in domestic refrigerator.

2. PHASE CHANGE MATERIAL SELECTION

Various sub zero (Below Ice Freeze temperature) Phase Change materials have been developed in the recent past, which form potential candidates for usage as storage device in fresh food & freezer compartment. The usage of dual temperature refrigeration cycle which consists of high temperature & low temperature refrigeration with appropriate PCM instead of conventional single low temperature refrigeration cycle has good potential for energy saving. The benefits come on two counts namely

A) By doing fresh food cooling by using high temperature refrigeration cycle during on time, and with off time prolonging by using PCM

B) By storing excess energy at high refrigeration temperature to be used subsequently as sub cool energy for running the relatively less efficient low temperature refrigeration cycle.

The above two benefits translate into improvement in Co-efficient of performance by about 20% or so. Also the increased off time due to storage of energy in the fresh food and freezer compartment gives better food preservation which helps improve the refrigerator performance.

3.MATHEMATICAL MODEL FOR HEAT LOAD CALCULATION

3.1 System Level Model

A mathematical model and simulation program have been developed for sealed system and compartment of a Phase Change Material (PCM) based refrigerator. The model is based on total kJ requirement for cooling the Freezer and Fresh food compartment independently. Simulation program has options for analyzing multiple evaporators including PCM heat exchanger, modifying sealed system configuration and varying damper opening.

Mathematical model: Input parameters for this model are tabulated in Table 1.

Table 1: List of input parameters to baseline a refrigerator.

Sr. No.	Input parameter	Sr. No.	Input parameter
1	Type of Refrigerant	6	Compressor curve
2	Pressure drop in evaporator, condenser	7	Compressor
3	Degree of Superheat & sub cooling	8	Compartments' percentage load sharing
4	Evaporator, condenser pressure	9	Compressor On/off time duration
5	Enthalpy drop in capillary tube	10	Compartments' temperature range

Assume for a cooling compartment at steady state, its energy content is Q_i at the end of ON duration and reaches Q_f at the end of OFF duration, where $Q_f > Q_i$. During OFF period, increase in energy content in the compartment is due to heat loss from ambient.

$Q_i + Q_l = Q_f$ Where $Q_l = t_{off} * W_l$

Here t_{off} is compressor OFF time duration/cycle and W_l is average heat leakage rate from ambient to cooling compartment.

$$Q_f - Q_i = Q_l = t_{off} W_l \quad \text{---------Equation 1}$$

During compressor ON time duration, evaporator has to do two tasks;

i) Bring down energy content from Q_f to Q_i

ii) Take care of heat loss from ambient to compartment during ON time duration

$$Q_{ev} = (Q_f - Q_i) + Q_l \quad \text{---------Equation 2}$$

Here it is assumed that Q_l is same for ON and OFF duration.

If W_e = evaporator capacity then

$$Q_{ev} = W_e \; t_{on} \quad \text{---------Equation 3}$$

It is assumed that average heat leakage rate W_l is constant during entire steady state of the refrigerator.

$$Q_l = W_l \; t_{on}$$ ---Equation 4

From equations 2, 3 and 4 $Q_f - Q_i = W_e \; t_{on} - W_l \; t_{on}$ ---Equation 5

Now equation 1 & 5 give $t_{off} \; W_l = W_e \; t_{on} - W_l \; t_{on}$ ---Equation 6

$$W_l \, (t_{on} + t_{off}) = W_e \; t_{on}$$

$$\frac{t_{on}}{(t_{on} + t_{off})} = \frac{W_l}{W_e}$$ ---Equation 7

Where $\frac{t_{on}}{(t_{on} + t_{off})}$ is equivalent to % ON time of the refrigerator.

From equation 8, it can be concluded that if compressor curve with on and off time is available, average leakage rate can be determined. In equation 8, W_e is determined from measured evaporator and condenser temperature, on compressor curve .It is assumed that leakage rate is constant for a refrigerator unit operating in same ambient conditions and slightly different inside temperatures too. For FZ & FF, separate leakage rate calculation, percentage share of FF & FZ should be known.

For calculating the cooling compartment heat capacity, it is assumed that during OFF time, air & food load inside the compartment remains unchanged.

$$M \, C_p \, (T_f - T_i) = Q_f - Q_i$$ ---Equation 8

Where $M \, C_p$ is heat capacity for a refrigerator, M Cp of a compartment is a combined heat capacity of air and food load, and T_f is average high temperature and T_i is average low temperature.

From equation 1 and equation 8 $Q_f - Q_i = Q_l = t_{off} \; W_l$ ---Equation 9

$$M \, C_p \, (T_f - T_i) = Q_f - Q_i$$ ---Equation 10

$$M \, C_p = t_{off} \, \frac{W_l}{(T_f - T_i)}$$ ---Equation 11

Hence $M \, C_p$ can be calculated for both cooling compartment e.g. FZ and FF compartments.

A simulation program has been developed in MS Excel macros with Visual Basic programming language to predict and optimize performance of the refrigerator with new sealed system. The program calculates kJ requirements for a baseline model based on given compressor ON time and evaporating capacity from compressor curve.

Configuring a new sealed system: After benchmarking baseline refrigerator model, next step is to select a particular configuration for the new refrigerator. For this, a user-friendly section is incorporated in the simulation program to choose a particular type of PCM refrigerator configuration. The section is the part of the input sheet shown in Figure 1. There are options to select and deselect damper and particular type of heat exchanger from the sealed system design. For example a 2-evaporator sealed system has no damper in the refrigerator hence air cannot move from FZ to FF and vice versa. There can be a direct air heat exchanger and a PCM heat exchanger in both FF & FZ compartment. In addition, it can have a sub cool PCM heat exchanger to absorb heat from refrigerant coming out of first capillary tube during discharging cycle. For a new configuration, there would not be any change in compartment parameters hence the parameters shown in Table 1 will remain the same .In order to compare the performance of baseline and new refrigerator, thermodynamic analysis of each cycle has been performed and presented through a graph as shown in Figure 2. The graph is updated as any design parameter changes in new cycles. New cycles may comprise of charging (high temperature) and discharging (low temperature) cycles. PCM details can be entered into the simulation sheet Details of thermodynamic properties of refrigerant at different locations and for different cycles are tabulated in the simulation program .

Optimizing for maximum energy saving: After benchmarking of baseline refrigerator, selecting exact configuration of new refrigerator, selecting PCM material and its freezing temperature, fitting the compressor curve and anchoring thermodynamic models in the simulation program, the performance of new refrigerator can be optimized. The details of PCM Cooling are given in Figure 3. The heat exchanger details are shown in Figure 4. The optimization portion in the simulation program is shown in Figure 5. Each of six design parameters has range based on physical constraints. Objective function is energy consumption and COP. The constraints are monitored through simulation program The excel add-in software based on Genetic Algorithm was used for thermal optimization. Details of heat exchangers like length, area, temperature, percentage cooling load sharing, heat transfer coefficient can be entered in the simulation program

3.2 Overall Energy Baseline / New PCM System Performance

Overall energy saving and comparison of baseline (basic) and new refrigerator performance can be seen from Figure 7.

3.3 Entitlement Study – Benchmark and New PCM Cycle

The theoretical estimation of the energy saving & COP improvement with the existing & new cycle is explained below in the Figure 6. The existing Cycle COP of 1.5624 changes to 2.007 / 1.808 for Charging / Discharging giving scope for energy savings with the new PCM based system. Based on this there could be potential of 8% savings in energy of the existing refrigerator model we benchmarked for the 9_9 coolest setting.

4.NEW CONCEPT REFRIGERATOR PROTOTYPE

The following are the broad categories of possibilities to improve COP with PCM:

1. Freezer Off Time prolonging & modifying leakage load on 24 hr basis by putting PCM in low temperature evaporator system in freezer.
2. Fresh food off time prolonging & modifying leakage load on 24 hr basis by putting PCM in additional high temperature evaporator system in fresh food (DUAL Evaporator with PCM)
3. By using PCM as in fresh food on high temperature evaporator system to separately cool fresh food (NO Damper) . This high capacity cooling shall have higher COP since refrigerant evaporating temperatures are typically –5 to 15 Deg F, which gives better COP. This may reduce Fresh food ON time
4. Sub cool energy transfer from high temperature evaporator system through media of PCM to low temperature evaporator system hence improving COP. This may reduce Freezer ON time .
5. Use damper for initial pull down of fresh food & freezer & then use dual evaporator cycle for cycling. This may help faster pull down.

The concepts we analyzed were combination of above & we concluded based on our Kilojoules based model that the combination of PCM in Freezer / Fresh food with extra sub cool PCM in Fresh food / Outside will give the best energy savings. Based on this concept the design schematic is shown in Figure 8. Also to operate the vapor compression cycle with this new design needs to have a new algorithm. The new algorithm takes into consideration the operation of valves to provide refrigerant to the required portions during the charging cycle and the discharging cycle. According to this algorithm required we prepared the hardware of the Sealed system.

5.REFRIGERATOR TESTING (New Concept)

Based on the above design we balanced the unit and checked the cycle system temperatures of the charging & discharging temperatures. The design consisted of having a modified Freezer (Main) evaporator with the PCM portion of heat exchanger added to it with associated capillary with a modified fan and air duct system. A new Fresh food (Second) evaporator with the PCM portion of heat exchanger with new fan and duct system was installed in the

Fresh food area . An additional PCM storage device heat exchanger was added outside the two chambers with a heat exchanger for latent heat release and storage during charging / discharging process. The various temperature parameters for vapor compression cycle and the freezer / fresh food load with the sensor temperatures were monitored and the refrigerator worked perfectly fine. The cycle balance with this new system was also done and testing of refrigerator power consumption was done. The various graphs of these readings are shown in Figure 9.

6. RESULTS AND DISCUSSIONS

The refrigeration cycle balance in terms of no liquid return to compressor was achieved in both the charging and discharging cycle . The gas quantity was also properly balanced for both cycles. The fresh food refrigeration temperature during the high temperature charging cycle was satisfactory. In this cycle the Fresh food evaporator, Fresh food PCM (Properly solidified) & Sub cool PCM (Properly solidified) cooling was good enough with a period of 12-13 mins time to maintain the fresh food temperature during charging / discharging & compressor off cycle. The food temperatures of the simulated propylene glycol load was found to be much better in terms of the narrow temperature band in which this could be maintained due to the inherent store & release capacity of PCM in the form of thermal storage. This means that PCM is effective in bringing down the fluctuations in the fresh food temperature, which is invariably seen in either single or dual evaporator systems without PCM. The refrigeration capacity delivered

by the high temperature charging cycle has been good enough to do cooling of the air with appropriate fan at a much lower time than 12-13 mins . The desired / calculated of heat transfer co-efficient for tube in tube out heat exchanger (FOR Fresh food PCM) **may** not be actually as per this & hence we could not get the desired fresh food cooled along with PCM solidification in 6-8 mins which Is the calculated time as per our model. Also the sub cool heat exchanger that was kept behind the refrigerator walls (to not add to the load of fresh food by putting it in) needed better insulation than the existing Vidaflex 15 mm insulation put but ideally this heat exchanger should be mounted between the outer sheet metal wall & PUF insulation area of refrigerator. This can be implemented in the final refrigerator design to give better sub cool benefit. Also tube in tube out design is not the best possible option & its secondary fin which we retrofitted from existing GE fin design could be more effectively designed.

In the discharging cycle the flow of refrigerant from the condenser out is directed through a sub cool (third) capillary wherein PCM in sub cool heat exchanger melts to sub cool the refrigerant from a partial liquid/gas mixture to become completely saturated liquid or further sub cooled liquid. Here the assumption that we made in the modeling of our refrigeration cycle was that mass flow rate of refrigerant does not reduce with change in status of refrigerant from a liquid / gas mixture to completely liquid or sub cooled liquid state. In the actual case since we did not have mass flow metering device we could not exactly pin point to this effect. But in the actual freezer application we could not see the theoretically calculated increase in refrigeration capacity of 8-12% on the airside. So in effect the freezer side on time of compressor never got reduced in any of the trials due to additional sub cool effect . Hence there maybe a reduction in mass flow rate which in net effect would not have given perceptible increasing in cooling due to sub cooling. Another aspect was the additional freezer PCM heat exchanger. It possibly acted as an additional load & also since the refrigeration temperature never reached in this heat exchanger to –22 Deg F to –15 Deg F the PCM could not fully get solidified. So in the process the Freezer discharging process on time was typically 38-39 mins when as per the model the calculated time was only 32-33 mins. Also the overall compressor off time was not changed from approximately 30-31 mins due to the in effectiveness of freezer PCM to cool during this time . So as per model the calculated off time of 40 mins could not be achieved. So the net effect was that overall we could not save any energy in the full cycle.

One good aspect of the test results was that the food temperatures were more stable for fresh food and freezer during the on / off cycling of the PCM based refrigerator in comparison to the conventional refrigerator. The hysteresis effect was also much narrow and broader for the PCM refrigerator compared to the conventional system.

We could easily claim good fresh food benefit & its energy saving potential only for fresh food since in this high temperature refrigeration cycle COP is much higher. But at a overall freezer / fresh food combination system energy savings need to be shown after further studies are done.

7.CONCLUSIONS

The side-by-side 25 Cu ft refrigerator prototype with a new dual PCM Based refrigeration cycle was made & demonstrated. The mathematical model for Side-by-Side refrigerator with Baseline kilojoules based load calculation was also made and demonstrated. The experiments done with the new prototype with PCM based refrigeration cycle gave very good & uniform fresh food / freezer temperature. Since the PCM in the fresh food was working in the desired temperature range of solidification & melting the cycling of fluctuations in food temperature was much lower than conventional single temperature refrigeration cycle. The freezer PCM did not work fully to the desired temperature range of solidification and melting which means that there could be improvements in the Freezer temperatures & also it would help in prolonging off time. There is further scope for improvement in this concept to get the energy savings calculated by the model by doing changes in heat exchangers (to improve U value) , cycle system (to improve Freezer PCM melt / freeze) and to tune the hysteresis temperatures of fresh food / freezer . Mass flow rate measurements for all new developed cycles would help a much more thorough engineering analysis of the new refrigeration systems. There would be scope also to optimize capillary and gas quantity of refrigerant for the new PCM based system, which also would help to maximize energy Savings.

NOMENCLATURE / ABBRIEVIATIONS

PCM –Phase Change Material
COP - Co-Efficient of performance
Q_i - Energy Content at end of ON duration
t_{off} - Compressor OFF time duration/Cycle
cooling area
Q_1 - Average Leak Energy
FF - Fresh Food
MC_p – Heat capacity of refrigerator
refrigerator
T_i - Average low temperature of air in refrigerator

TS –Thermal Storage
KJ –Kilojoules Energy
Q_f -Energy Content at end OFF duration
W_l –Average heat leak rate ambient to
t_{on} -Compressor ON time duration/Cycle
FZ -Freezer
T_f - Average High temperature of air in

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Figure 1 – Mathematical model input screen

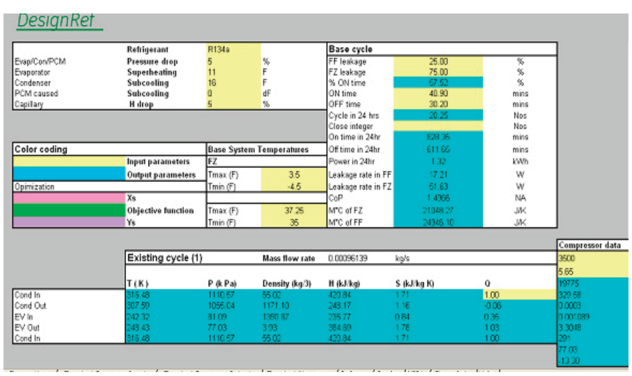


Figure 3–Mathematical model PCM Cooling Details

From Themodynamic graphs		
Evap. Cooling Cap. (base)	143.18	Watt
Evap. Cooling Cap. (discharging)	157.13	Watt
Evap. Cooling Cap. (charging)	260.87	Watt
Power used in subcooling (charging)	19.02	Watt
Power available after SC (charging)	241.84	Watt
PCM H/X Avail. Capacity	1.00	fraction
Subcooling % of discharging capacity	12.11	%

Figure 2–Thermodynamic Cycle with & without PCM

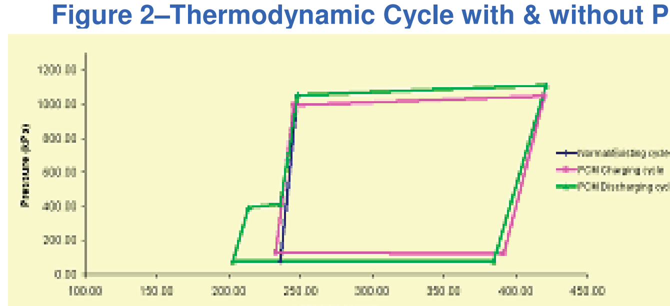


Figure 4–Mathematical model heat exchanger Details

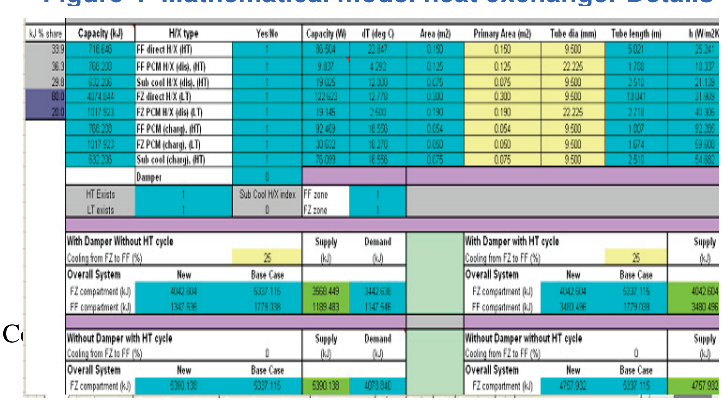


Figure 5 – Mathematical model Kilo joule Optimization

	Damper	0		
HT Exists	1	Sub Cool HX index	FF zone	1
LT exists	1	0	FZ zone	1

With Damper Without HT cycle			Supply	Demand
Cooling from FZ to FF (%)		25	(kJ)	(kJ)
Overall System	New	Base Case		
FZ compartment (kJ)	4042.604	5337.115	3560.449	3442.630
FF compartment (kJ)	1347.535	1779.038	1189.483	1147.546

With Damper with HT cycle			Supply	Demand
Cooling from FZ to FF (%)		25	(kJ)	(kJ)
Overall System	New	Base Case		
FZ compartment (kJ)	4042.604	5337.115	4042.604	4460.561
FF compartment (kJ)	3480.496	1779.038	3480.496	2119.080

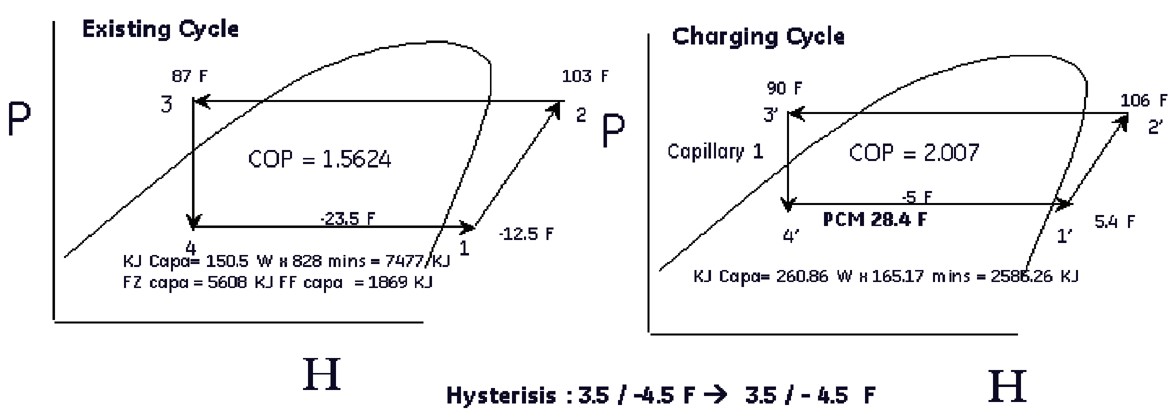
Without Damper with HT cycle			Supply	Demand
Cooling from FZ to FF (%)		0	(kJ)	(kJ)
Overall System	New	Base Case		
FZ compartment (kJ)	5390.130	5337.115	5390.138	4070.040
FF compartment (kJ)	2132.961	1779.038	2167.205	2119.060

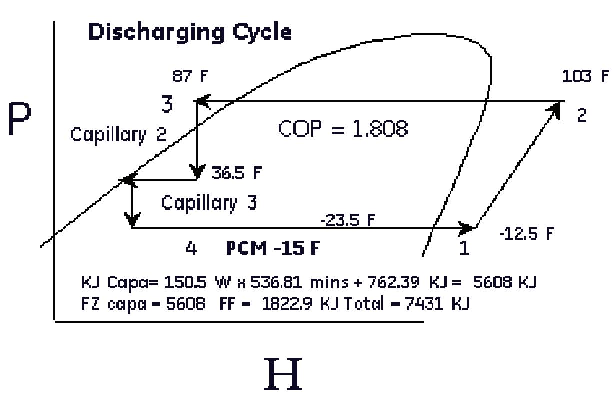
Without Damper without HT cycle			Supply	Demand
Cooling from FZ to FF (%)		0	(kJ)	(kJ)
Overall System	New	Base Case		
FZ compartment (kJ)	4757.932	5337.115	4757.932	3442.630
FF compartment (kJ)	0.000	1779.038	0.000	NA

Figure 7 – Mathematical Model Energy Savings

% Energy Saving 10.424				
New system			Basic System	
ON	37.50	min	40.90	ON
OFF	40.50	min	30.20	OFF
Energy in 24hr	1.183	kWh	1.321	Energy in 24hr
CoP	1.7663	NA	1.4966	CoP
Capacity	7230.837	kJ	7116.154	Capacity
Cycles in 24 hrs	18.46	Nos.	20.25	Cycles in 24 hrs
% ON	48.08	%	57.52	% ON
FF	2167.205	kJ	1779.038	FF
FZ	5390.138	kJ	5337.115	FZ
LT capacity	5221.683	kJ	7116.154	LT capacity
HT capacity	2009.154	kJ	0	HT capacity

Figure 6 – Entitlement for Cop Improvements and Energy Savings





	9_9 Old	New 9_9
On time - Charging	40.9	8
On time - discharge		26
Off Time	30.2	35.75
Total time/cyle	71.1	69.75
Cycles /day	20.3	20.6
Watts I/p charge	96	130.0
Watts I/p discharge		96.0
% On time	58%	49%
Ambient Deg C	21	21
Power Kwh/day	1.33	1.22
% Savings		8%

Figure 8 – New PCM based Refrigeration Cycle

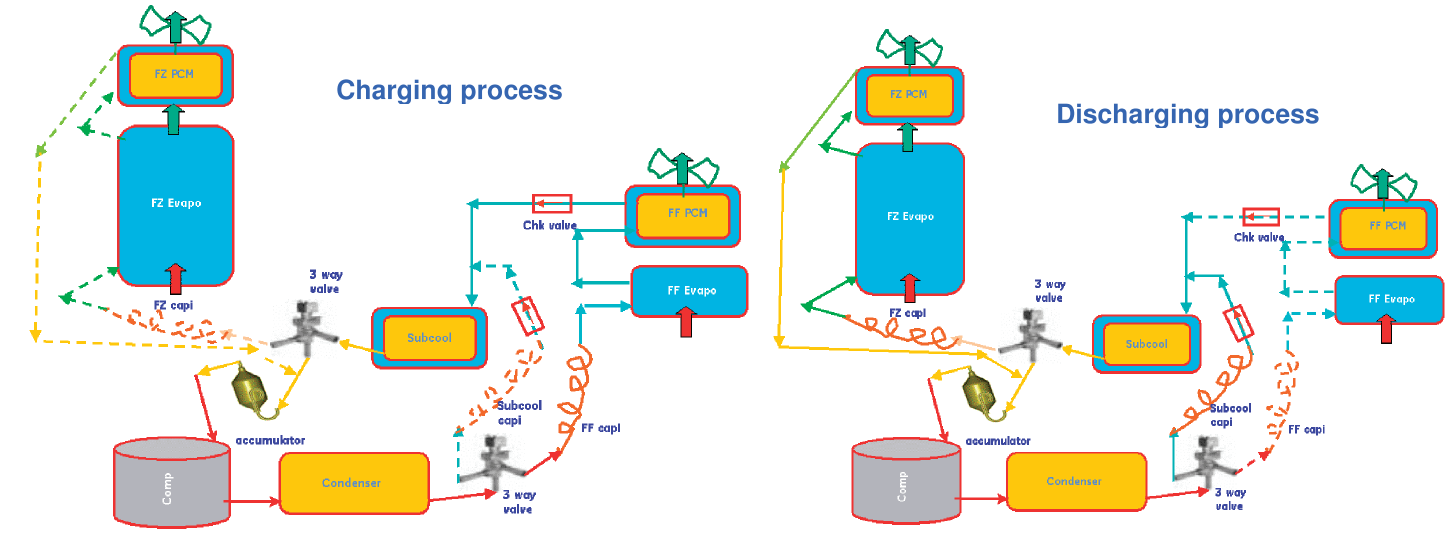


Figure 9 - New Refrigeration Cycle Temperature Charts