Design of a 126 Litre Refrigerator/Freezer Commercial Prototype

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Abstract

Designing a thermoelectric (TE) refrigerator/freezer to cost and performance targets set by refrigerator manufacturers is a difficult task which requires innovation and creative design, coupled with sound engineering practices.

A 126 litre refrigerator, incorporating a 36 litre freezer compartment, was designed, built and performance tested to strict cost, efficiency and performance targets set by Matsushita Refrigeration Company (MARCO). The design of this refrigerator will be explained with a detailed description of the materials and components utilized. A key component to meeting efficiency targets was the liquid coolant used with Hydrocool's high performance TE heat exchangers. The choice of insulation levels and materials is another key factor as well as high efficiency power supplies.

Introduction

Traditionally the application of thermoelectric cooling technology to mass market domestic refrigeration products has been limited to niche applications such as mini-bars, wine storage cabinets and truck cabin refrigerators. These applications have been addressed by National Panasonic (MARCO) using Hydrocool's 1st generation liquid coolant heat exchangers designed for thermoelectric modules.

These applications have tended to be small in heat load and for cooling only, i.e. no freezing capability. As such, their efficiencies have rivalled that of vapour compression technology with the added bonus of light weight, low noise and no CFC's.

Hydrocool has been further developing its heat exchange technology and embarked on a collaborative project with Matsushita Refrigeration Company to test the capability of thermoelectrics in a mass market refrigerator/freezer. The unit chosen was a 126 litre unit which included a 36 litre freezer. A photo of this refrigerator is shown below in Figure 1.

Figure 1. 126 litre Refrigerator/Freezer

The aim of the project was to investigate the design processes and compromises involved in developing a fully functional commercial prototype that met stringent power consumption targets as well as manufacturing cost targets.

The critical specifications for the prototype were:

Item	Condition	Target Performance	Hydrocool Performance
Cooling Power	30°C ambient	Freezer: -25°C Fridge: 0°C	Freezer: -25°C Fridge: 0°C
Energy Consumption	25°C ambient 5°C in fridge -18°C in freezer	490 kWhr/yr	513 kWhr/yr
Noise	1m from front 1m above floor	20 dB	23 dB
Defrosting	30°C ambient	No performance dew clogging freezer	Complies at 25°C, 70%RH
Dew condensation	30°C ambient , 85%RH, 5°C in fridge, -18°C in freezer	No dew on fridge surface	Complies
Parts cost		170 USD	218 USD

The practical considerations involved in taking a design from experimental to commercial are highlighted in this set of specifications and impose significant additional constraints on the design process. This paper will describe these constraints with the aim of providing a better understanding for those in the research fields when designing/building commercial prototypes.

Hydrocool System

The Hydrocool system uses liquid coolant on both cold and hot sides of the TE module to increase the heat transfer coefficients [1]. Highly efficient heat exchanger designs have been developed that have low thermal resistances even under relatively low flow rates (important in refrigeration where ancillary power for pumps and fans are included in system COP calculations).

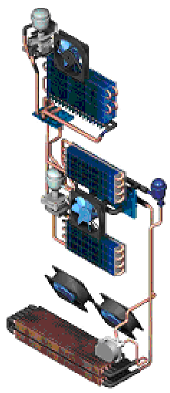

Figure 2. Hydrocool system

A schematic of the Hydrocool system developed for this project is shown below in Figure 2. Conventional fin/tube heat exchangers with fans are used for heat transfer between air and liquid.

Design – Energy Consumption

The first design consideration was energy consumption. An initial modeling analysis was carried out, using known thermal resistance values for the Hydrocool HC3 heat exchanger soldered directly to the TE module and assumed values for fin/tube heat exchangers. Power supply efficiency and fan and pump powers were assumed from previous experience and dry pipe loads provided by National Panasonic. This analysis showed that thermoelectrics could not achieve the target energy consumption while conventional polyurethane insulation was used. The heat loads were simply too high.

	Heat Loads (W)
Freezer cabinet	18.6
Freezer fan, dry pipe	1.8
Freezer Power consumption (COP=0.30)	68.0
Fridge cabinet	16.65
Fridge internal powers	3.2
Fridge Power consumption (COP=1.15)	17.26
Ancillaries (pumps, fans, dry pipe)	8.7
Total Power DC	94.0
Total Power AC (efficiency 85%)	110.6

A power consumption of 110.6W continuous equates to 969 kWhr/yr. This is well in excess of the 490 kWhr/yr target so clearly an alternative design approach has to be taken. This approach reduces ancillary power by providing extra control intelligence to switch the dry pipe on only when required (in conditions of high humidity), rather than continuously running (saving 3.4W heat load) and also by reducing the heat load in the freezer by substituting higher levels of insulation using vacuum insulation panels (VIP).

The extra control intelligence is available at no cost because a microprocessor controlled power supply will be used. However additional component cost will be incurred for a humidity sensor and a control valve. VIP panels are becoming commercially available and MARCO itself uses them in some products. They will also contribute to a higher parts cost.

The final energy consumption design is shown in the table below:

	Heat Loads (W)
Freezer cabinet, fan	7.7
Freezer Power consumption (COP=0.30)	25.67
Fridge cabinet	16.65
Fridge internal powers	2.3
Fridge Power consumption (COP=1.15)	16.48
Ancillaries (pumps, fans, dry pipe)	5.3
Total Power DC	47.45
Total Power AC (efficiency 85%)	55.82

A power consumption of 55.8W continuous equates to 489 kWhr/yr, meeting the energy consumption specification.

The key assumptions that have been made are regarding VIP performance, power supply efficiency, COP's of TE devices (particularly in the freezer) and ancillary power levels. Each of these will be discussed briefly.

Manufacturers data is available for VIP and modeling indicated that 50mm thick panels enclosing the 36 litre freezer space will theoretically provide a 5.6W heat load. Of course when these panels are assembled into a box shape there are many sources of heat loss through corner and edge effects and the performance of the resulting construction is compromised to some extent. In addition there are unavoidable losses through door seals. Heat load measurements carried out after construction showed that the VIP freezer had a heat load of 7.9W.

Because the temperature differential across the freezer TE device is relatively high the COP will consequently be low. Two alternative heat flow paths are possible – the heat extracted from the freezer can be transferred into the fridge cabinet (at a dT of 23°C) and then from the fridge cabinet to ambient (at a dT of 20°C) or else direct to ambient (at a dT of 43°C). Thermodynamically the heat paths are virtually equivalent and a decision on which path to take rested on the performance of commercially available TE modules.

A staged module was considered for the 43°C differential, where the fridge heat would be handled with two Frost 75 modules.

Alternatively a Frost 75 single stage module could be used between the freezer and fridge and an additional Frost 75 module provided in the fridge circuit (giving 3 fridge modules) could dispose of the freezer heat and electrical input power to the freezer module. The heat loads were such that all four modules could operate at close their peak efficiency. This arrangement was used since it resulted in no loss in efficiency and avoided the requirement for multiple stage modules.

Extensive testing of the Hydrocool HC3 at ambient and chilled temperatures down to 5°C had provided detailed performance data. However its performance at freezer temperatures of –18 C with relatively viscous fluid was unknown. In addition the level of pump power required to achieve a reasonable flow rate was unknown with viscous liquid.

The liquid chosen as a heat transfer fluid was Freezium, a potassium formate solution which is liquidity to -50°C depending on concentration. It's viscosity is 1.90mm^2/s at –20°C (much better than alternative products such as propylene glycol) and has a reasonable specific heat of 2.78kJ/kg°C. It is an ideal low temperature heat transfer fluid.

The level of ancillary pump and fan power is very important particularly for those units located inside the fridge and freezer. These devices not only consume power but also contribute to the heat load. Of course higher air and liquid flows increase heat transfer coefficients and therefore reduce thermal resistances but there is an optimum point for each design. The optimum point will vary depending on other variables such as the surface area of the heat exchanger, the efficiency of air flow paths, tube size and pressure drop, fin spacing and number of rows. The characteristics of each device in the system must be known explicitly in order to optimize the complete design.

A choice must be made early in the design process on how the optimization is done, either by measuring the characteristics of many components or by building prototypes and testing in situ. Because of the tight timeframes in this project some characterization was done on individual components but optimization of pump and fan power levels was done in situ once prototypes were built.

Generally the optimum points occurred at very low power levels for internal devices but at higher power levels for those located outside the cooled spaces.

Of critical importance in the design is the power supply. It must firstly convert AC power to DC and then deliver a variable current in response to the prevailing conditions. Efficiencies well over 90% are common in large power converters (at the several kW level) but are difficult to achieve in small power supplies. The power supply for this refrigerator had a steady state demand of 50W but also requires a capacity of 300W for pull down purposes. A microprocessor controlled switched mode power supply was specially designed for this purpose with an efficiency curve as shown below in Figure 3.

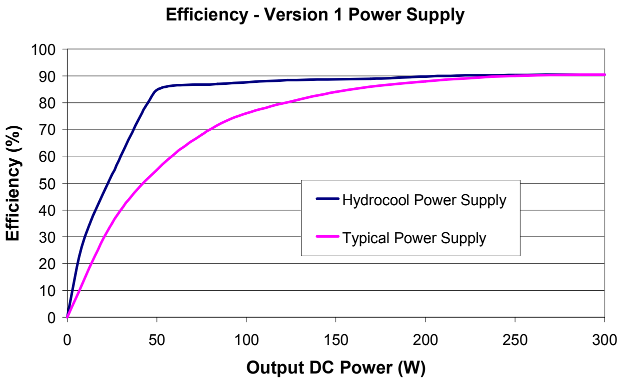

Figure 3. Power supply efficiency

As can be seen the power supply has reasonably good efficiency at full power and is able to retain a large proportion of that efficiency right down to steady state conditions at 17% of full power. Most commercial power supplies cannot retain anywhere near the efficiencies at low power levels shown above.

This is a major issue retarding the application of thermoelectrics to consumer appliances where efficiency is important. Sacrificing 15% of efficiency just so the device can be run from mains power is a significant penalty and makes it more difficult to compete with conventional vapour compression refrigeration.

A microprocessor controlled power supply is very useful in a refrigerator design because it can be used not only for relatively complex control algorithms (PID was used in this prototype) but also for many additional features such as monitoring relative humidity for switching dry pipes on, defrosting strategies that are consistent with door opening intervals and prevailing environmental conditions, graphical displays of conditions inside the refrigerator, user interfaces for temperature settings, diagnostics on the performance of the system, alarms and maintenance requirements.

An additional benefit that PID control brings is that the cooling power can be modulated to suit environmental conditions. Thus TE cooling is never switched off completely (unlike compressor refrigerators which cycle on and off) and internal temperatures are maintained at very constant levels. The internal heat exchanger surface temperatures are maintained much closer to design temperatures than in compressor refrigerators where the evaporator plate is usually at –30°C (and therefore extracts most of the moisture from incoming air). The TE design therefore has a constant temperature, moderate humidity internal environment which is preferable for food storage and extends the shelf life of food products.

Design – Commercial Constraints

The overriding commercial consideration is cost. The marketplace for domestic appliances is extremely competitive and very cost conscious. In our design the single largest cost item is the power supply. Costs are evenly spread across the whole design, as shown in the table below, although the liquid circuit and heat exchanger sections consist of several large and many small components.

Cost reductions are likely in the TE system with improvements to Hydrocool manufacturing techniques and cheaper TE modules becoming available.

Section	Cost $US	%
Power supply	60	28
TE system	56	26
Liquid circuit	42	19
HEX, fans	60	28
Total	218	100

There are a range of other commercial constraints to the design, some associated with the task of fitting a new type of cooling technology into an existing cabinet designed for a compressor, and some which are a result of moving from a lab prototype to a real, commercial environment. Considering the effects of condensation, icing up of freezer heat exchangers, ensuring 10 year minimum service life, noise levels and the ability to operate in extreme environmental conditions are some of these which will be discussed below.

Spatial constraints were the most obvious and immediate problem early in the design phase. A conventional cabinet was used which had a space at low level available for the compressor. No space was allowed for a hot side heat exchanger as these refrigerators typically use the metal casing as a condensor heat exchanger. The hot side heat exchanger and fans were located in this space even though it was not ideal. The power supply was also located here to minimize any contribution to noise at full power.

Condensation on the cabinet outer surface is not acceptable and to prevent this effect in conventional refrigerators a small copper tube is mounted inside the cabinet along the line of the door seals, where the surface is coldest. This prevents condensation but consumes extra energy to pump gas to these areas and inevitably some of the heat leaks back into the refrigerated space. Our design used these tubes but pumped warm liquid through them. Critically, we added a humidity sensor as well as an ambient temperature sensor to the control system and only ran the dry pipe when environmental conditions required it.

Icing of freezer heat exchanger fins occurs because of the extra moisture introduced with air at every door opening. After a fixed time period defrosting is programmed to occur and is achieved by activating an electric heater situated below the heat exchanger. This places a further cooling load on the freezer circuit at regular intervals.

Because the TE technology is new to this application reliability is a major design issue. Hydrocool uses a soldered joint between the TE module and HC3 and therefore any thermal stresses in the HC3 will be transmitted through to the module. To ensure that these stresses would not affect the life of the TE module an accelerated reliability test rig was set up where modules were repeatably cycled from zero to the full design temperature difference for both fridge and freezer conditions. An average of 25 fridge door openings and 8 freezer door openings per day was used to calculate equivalent service life in years. In the time available several modules exceeded 10 years and one exceeded 20 years in simulated service. Of the nine TE module assemblies tested not one suffered any performance degradation.

Noise levels are already very low in good quality conventional compressor refrigerators. Thermoelectrics is noiseless however the external cooling fans and liquid pumps do provide noise. The hot side heat exchangers and fans were located at low level and at the back of the refrigerator. With very little design effort the noise levels were maintained close to the target levels and some minor modifications are necessary to achieve the target specification. 20dB is very quiet indeed (the background reading in an anechoic chambers is around 17dB) and is almost undetectable with the human ear.

The design must not only be capable of operating at very efficient levels for the steady state energy consumption test but must have sufficient power to cope with extreme environmental conditions. Refrigerator manufacturers have extreme “Recovery tests” where the ambient temperature is set to 35°C and humidity to 85%RH. The fridge is loaded with bottles of beer and the freezer with ice cream. The fridge door is opened regularly over a 12 hour period with cold beers removed and replaced with warm bottles. At the end of this period the fridge and freezer are allowed to “recover” as in an overnight phase. By next morning all internal temperatures must have returned to normal.

Test Results

The table below summarizes the prototype refrigerator performance.

Freezer cabinet heat load	7.9W
Freezer power load (fan,pump)	0.8W
Fridge cabinet heat load	16.4W
Fridge power load (fan,pump)	0.9W
Total heat load	26.0W
Total AC power consumption	58.6W
Overall COP	0.44

In the Recovery test the prototype performed at a similar level to a compressor driven refrigerator of the same size.

Components

The main components of the system are listed in the table below.

	Parts	Supplier
Freezer		
TE module	1 x Frost 75	Kryotherm
TE heat exchanger	HC3	Hydrocool
Pump	MM9-561	Panasonic
Fan	AD1212DB	ADDA
Heat exchanger	NR-B13-TA	MARCO
Fluid	Freezium -60	Kemira
Insulation	VIP	Advantek
Dry pipe	Hot water (valved)	
Defrost	Heater wire	MARCO
Fridge		
TE module	3 x Frost 75	Kryotherm
TE heat exchanger	HC3	Hydrocool
Pump	MM9-561	Panasonic
Fan	AD1212LS	ADDA
Heat exchanger	2 x AF-125110	MARCO
Fluid	Freezium -15	Kemira
Insulation	Urethane	MARCO
Dry pipe	Hot water (valved)	
External		
Convector	HC3	Hydrocool
Pump	MM9-561	Panasonic
Fan	2 x AD1212MS	ADDA
Heat exchanger	12 tube Mesabi	Mesabi
Fluid	Freezium -15	Kemira

Conclusions

Carrying out this project provided several valuable lessons. It showed that innovative and creative design is necessary to achieve performances close to compressor driven refrigeration. Interestingly the cost comparisons were reasonable, indicating that thermoelectrics can be cost competitive, with an estimated cost only 28% higher than target. There are several potential avenues for cost savings and with further work this differential can be reduced.

However, compressor performance becomes more efficient as heat loads increase and for the larger domestic refrigerators (300-400 litres) a higher ZT TE module will be required to compete.

The process of moving from a laboratory prototype to commercial prototype is difficult with many design constraints. It is a necessary step however because it forces design issues to be confronted and solved.

The key to high performance TE refrigeration is in managing the thermal resistances throughout the heat flow paths and Hydrocools high efficiency HC3 TE heat exchanger is critical to success.

References

1. Attey, G., “Enhanced Thermoelectric Refrigeration System COP Through Low Thermal Impedence Liquid Heat Transfer System,” *Proc 17th International Conference on Thermoelectrics;* Nagoya, Japan, May 1998 pp 519-524.