The Development of Low Energy Integrated Commercial Refrigeration

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ABSTRACT

This paper describes the work carried out between April 2004 and September 2005 under the title "The Development of Low Energy Integrated Commercial Refrigeration Technology". The project brief was to investigate a new supermarket refrigeration concept named the "Integrated Chilled Water Loop" or ICWL and to compare its performance to refrigeration systems described in an EA Technology study. This involved constructing a supermarket refrigeration test rig, choosing a refrigerant, monitoring the performance of the test rig and comparing it to that modelled in the EA Technology study.

The ICWL is effectively a cascade refrigeration system consisting of a water chiller and a chilled water loop which cools low temperature and high temperature condensing units which in turn provide the store refrigeration.

Five refrigerants were compared, the first being the synthetic HFC refrigerant, R404A. The rest were natural hydrocarbon refrigerants. The best performance was obtained from a previously untested hydrocarbon blend. This performed, in one case, 20.5% better than R404A.

In comparison with the EA Technology models, the ICWL system was seen comparable in performance to an optimised DX system and "System 2", a refrigeration concept similar to the ICWL. It was shown that with an optimised chiller, the ICWL could exceed the performance of these systems.

1. INTRODUCTION

The technology investigated during this project is named the *"Integrated Chilled Water Loop"* or *"ICWL"*. It is an energy efficient and environmentally friendly supermarket refrigeration system intended for use with natural refrigerants. It makes use of some of the outputs from Annex 22 of the International Energy Agency Heat Pump Programme. Annex 22 dealt with heat pumps, air conditioning and refrigerating systems using natural working fluids [1]. The UK Annex 22 work programme, carried out by EA Technology focussed on supermarket refrigeration systems using natural refrigerants [2].

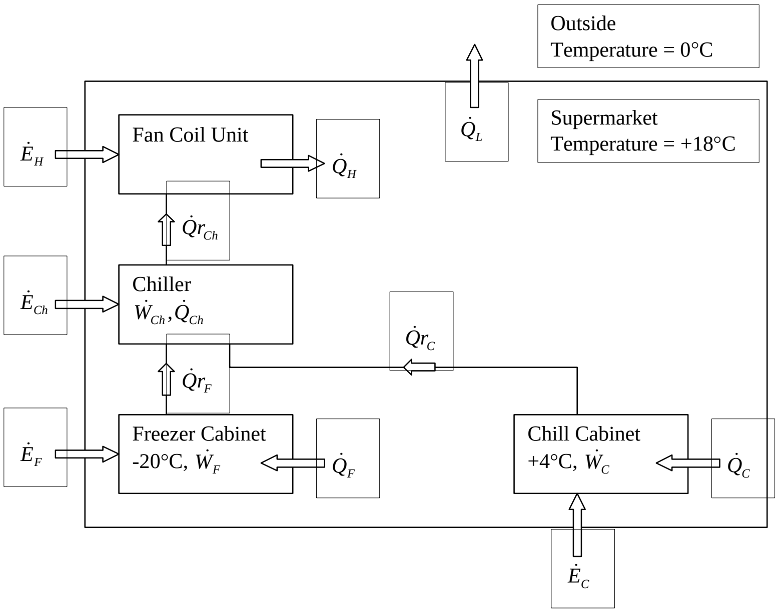
Part of the work was to construct computer models of various innovative supermarket refrigeration systems and analyse their performance compared to current technology. This work is described in a paper "A Supermarket Refrigeration and Heating System using Hydrocarbon Heat Pumps and an Ammonia chiller" [2].

The ICWL consists of a water chiller, a chilled water circuit, water cooled condensing units and an air handling unit. There is the option to add a hot water capability by incorporating heat recovery to the chiller.

The chiller provides water at a temperature of 7°C and the system is designed for a return temperature of 12°C, allowing the use of chilled water cooled air conditioning systems. The refrigeration condensing Units also reject their heat to the Chilled Water Loop. In a supermarket this would consist of chilled and frozen food display cabinets and storage.

Hot water can be generated by the use of a de-superheater or heat recovery condenser on the chiller. From a simple energy balance it can be seen that the store's heating can be provided if the total refrigeration and chiller absorbed electrical power exceeds the heating requirement.

Figure 1.1. Store Energy Balance



The Objective of this project was to construct a test rig consisting of all the elements of a supermarket refrigeration system and then to carry out various tests with the following intended outcomes:

- To prove the ICWL concept and provide performance data for comparison to that presented in the EA Technology Paper.
- To make a comparison between different natural refrigerants as well as between natural refrigerants and synthetic refrigerants (specifically R404A) in the system, allowing a choice of refrigerant or refrigerants made for use in the further development of the system.

2. EXPERIMENTAL PROCEDURE

2.1. Refrigerant Testing

One of the objectives of the project was to quantify the efficiency advantage of natural refrigerants over synthetic refrigerants. Therefore, the first task was to establish a performance baseline for the system using the synthetic refrigerant, R404A. After that, a series of natural refrigerants were tested as follows:

Table 2.1. Natural Refrigerants to Test

Name	Constituents
Care 40	Pure R290 (propane)
Care 45	Pure R1270 (propene)
Care 50	R290 (propane) and R170 (ethane)
Experimental Blend	R290 (propane) and R1270 (propene)

The test program for all of these refrigerants was the same. The first stage was to correctly charge all elements of the test rig other than the chiller with the refrigerant under test. The chiller was always run on R404A in order to keep the chilled water constant throughout all the tests. Having correctly charged the system, the two display cabinets and the Air Handling Unit were moved to the Test Chamber. The Test Chamber was set to conditions corresponding to EN441 Test Class 2 [3].

With the cabinets and Air Handling Unit in the chamber, the cabinets were loaded. In the case of the Chill Cabinet, this involved stacking the shelves with bottles of water and gel-packs to simulate the food with which it would be loaded in a supermarket. In the case of the Freezer Cabinet, this involved loading it with 4 buckets of ice. The internal temperatures of the buckets of ice and the gel packs were monitored to simulate the product temperature.

With this setup completed, the system was run until steady state conditions were reached. The chiller was run in heat recovery mode. During the test the flow rates through each piece of equipment were noted. Carrying out each test in this way would allow data for each test to be analysed to provide a comparison between each refrigerant.

2.2. Methods of Analysis

During each test, system temperatures and compressor electrical energy use were monitored. These were used to calculate the Heat Rejected, the Coefficient of Performance (CoP), the Compressor Electrical Power and the Cooling Capacity of each element of the system. In order to compare performance across the tests, Cooling Capacity and CoP were used.

The heat rejected (Q_r) was calculated from the temperature difference in the chilled water onto and off the particular condensing unit, this along with the compressor energy consumption (E) was used to calculate the CoP for an entire test as follows.

$$CoP = \frac{Q_r(kWh) - E(kWh)}{E(kWh)}$$

In order to calculate the compressor electrical power, the compressor electrical energy data was examined and the compressor runs isolated. The gradient of the compressor electrical energy graph was assessed during these runs to obtain the compressor power. In order to calculate the cooling capacity, the rate of heat rejection during each of these runs was evaluated. The rate of heat rejection $(\dot{Q}_r)$ in the data interval between two times, t1 and t2 is calculated as follows.

$$\dot{Q}_r(kW) = \Delta T(K) * \dot{V}(l/s) * r(kg/l) * c(kJ/kgK)$$

$\dot{V} = chiller\ water\ flow\ rate$

$r = density\ of\ water$

$c = specific\ heat\ capacity\ of\ water$

where

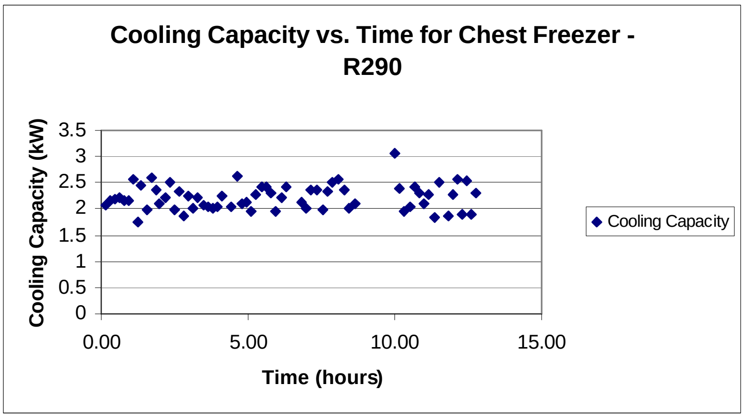
$$\Delta T = \left(\frac{(T8_{t1} - T7_{t1}) + (T8_{t2} - T7_{t2})}{2} \right)$$

which is the average difference between T7 and T8, the water temperatures onto and off the condensing unit during a test interval. The value $\dot{Q}_r$, above is the rate of heat absorption from the water during one data interval. The Compressor Electrical Power for the corresponding interval was subtracted from this to give the Cooling Capacity for the interval. Due to the large volume of data, a macro was written to carry out the Cooling Capacity calculation. The generalised overall steps taken by the finished Macro were as follows.

- Search the compressor power data for the next compressor run and calculate the gradient in each interval during the run to give compressor electrical power.
- Use the beginning and end time of the compressor run to search for the corresponding heat rejection to the water and calculate the rate of heat rejection, $\dot{Q}_r$ for each interval as described above.
- Cooling Capacity (kW) = $\dot{Q}_r$ (kW) – Compressor Electrical Power (kW).
- Loop previous statements until end of data is reached.

Once the cooling capacity for each unit in each test had been calculated, a simple plot was made of the cooling capacity vs. time. The cooling capacity should appear as a straight line when plotted against time.

Figure 2.1. Example of Cooling Capacity vs. Time (Freezer Cabinet; R290)



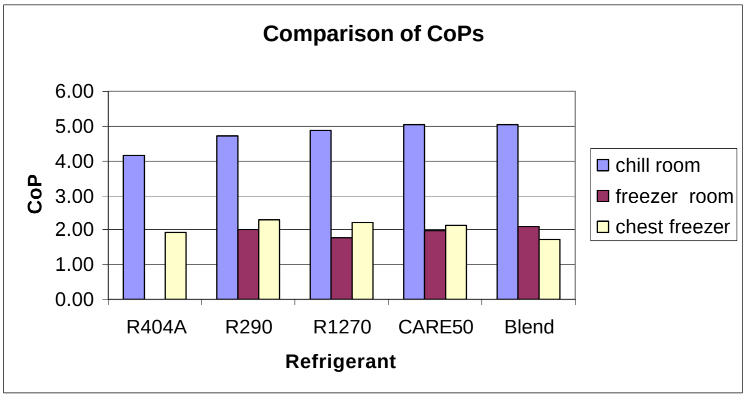
This graph shows a reasonable correlation between the data and the straight line suggested by the theory. The table below shows the results obtained for CoP and cooling capacity compared to the theoretical values obtained from the relevant compressor Manufacturers data.

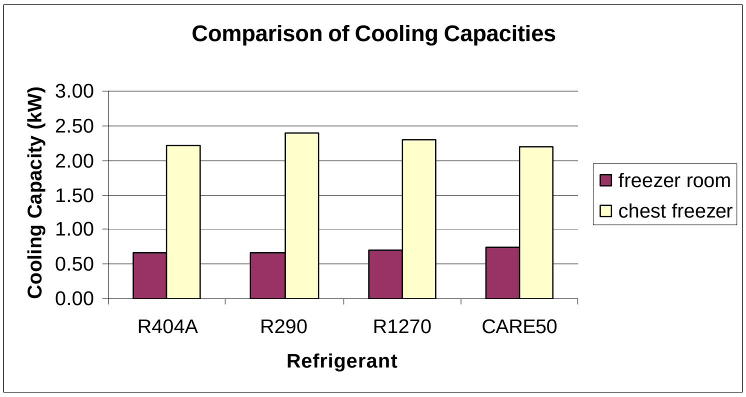
Table 2.2. Tabulated CoP and Cooling Capacity Results

Refrigerant	CoP					
	chill room		freezer room		chest freezer	
	measured	theoretical	measured	theoretical	measured	theoretical
R404A	4.13	3.97		2.11	1.93	1.92
R290	4.73		2.03		2.30	
R1270	4.89		1.79		2.21	
CARE50	5.02		1.99		2.15	
Blend	5.02		2.08		1.74	

Refrigerant	Cooling Capacity (kW)					
	chill room		freezer room		chest freezer	
	measured	theoretical	measured	theoretical	measured	theoretical
R404A		1.28		0.91		2.41
R290			0.67		2.21	
R1270			0.67		2.39	
CARE50			0.70		2.29	
Blend			0.74		2.20	

Figure 2.2. Graphical CoP and Cooling Capacity Results





The tabulated results contain a number of cells which have been struck through. In the "measured" columns, this is where the data was either not calculable or not sufficiently reliable to be presented. In the "theoretical" columns, this is because Manufacturer's data is only available for R404A refrigerant.

This does allow a good comparison to be made between the refrigerants. The first thing to compare is the measured R404A CoPs and their theoretical values. The result here is impressive in that the

Freezer Cabinet CoP is only 0.5% away from its theoretical value. The Chill Room CoP is 4% away from its theoretical value, again an impressive result. This gives validity to the CoP results obtained, both in the R404A case and with the other refrigerants. The fact that the values should be different at all is explained by the fact that it is impossible to size evaporators and condensers accurately enough to achieve the exact design evaporating and condensing temperatures. Changes in these temperatures lead to changes in CoP.

In comparing the different refrigerants, it can be seen that in the case of the Chill Room and the Chest Freezer, the CoP improved when moving onto the first Natural Refrigerant, R290. This confirms the hypothesized efficiency improvement. In the case of the Chill Room and the Freezer Room, the CoP improved as the tests progressed and the best CoP was achieved when using the blended refrigerant. This is not the case with the Freezer Cabinet where the CoP appears to worsen as the Natural Refrigerant tests progress. This is believed to have occurred due to the fact that the Freezer Cabinet compressor was oversized for the cabinet. This over sizing did not affect the performance adversely during the R404A test and simply caused a lower than design evaporating temperature.

On moving to the first Natural Refrigerant, the CoP does improve but then appears to worsen whilst it improves in the case of the Freezer Room. This is because, as the capacity increased too far, the evaporating temperature dropped, leading to premature icing of the evaporator and poor system performance, sometimes even cut-outs due to the low pressure switch.

Therefore, we can conclude from the CoP results that the move to Natural Refrigerants has caused a significant efficiency improvement, it the best case, a 21.5% change (Chill Room, R404A to Blend). The Chill Room results suggest that the blend is the best refrigerant. This is supported by the Freezer Room results although in this case the theoretical CoP for R404A was never exceeded. The Chest Freezer results are ignored due to the above arguments.

The cooling capacity results appear to support this conclusion in the case of the Freezer Room where the greatest capacity is achieved with the blended refrigerant. The Chest Freezer results are again ignored due to the above arguments. The cooling capacities, unlike the CoPs, never reached their theoretical figures. This is because the calculations failed to assess the full extent of heat rejected to the water. It therefore must be stressed that these values are intended as an indication in order to make comparisons between the tests and not an accurate and definitive measure of Cooling Capacity.

2.3.Comparison to Annex 22 System

Using the best achieved CoPs for Low Temperature and High Temperature, along with Manufacturers chiller data, a simple comparison can be made between the practical set up and two supermarkets modelled in the EA Technology Paper. This comparison shows that based on the results obtained from this project, the ICWL can compete with both Annex22 System 2 and the modelled DX system. The ICWL total power input is only 9.3% greater than Annex 22 System 2 and 6.1% greater than the DX system. This comparison is made ignoring all fans, lighting, defrost and other electrical ancillaries which will be common to all systems.

Looking at the CoPs down the table, this project has achieved similar CoPs to those predicted by the EA Technology Paper for the Low Temperature and High Temperature Units (Chill and Freezer). In fact, The CoP of the Low Temperature units is better than that predicted but this is partially offset by the CoP of the High Temperature units which is not so good. The main point to draw is that the values are comparable so the performance modelled in the paper is being observed. This is a very good result for a first prototype system. With further work these performances could be improved until they exceed the Annex 22 figures.

The chiller is a separate issue with the CoP 1.36 lower than the Ammonia chiller modelled in the EA Technology Paper. Due to the fact that the chiller under test was run in heat recovery mode for the entire project, no practical data was available for cooling only mode which is what would be required under similar conditions. For this reason, Manufacturer's data is used for the chiller, based on the test conditions. This provides a very modest CoP which could be improved considerably, not least by the use of natural refrigerants.

If the greatest CoP improvement seen by the use of the blended refrigerant over R404A was repeated in the chiller (21.5% CoP improvement), the chiller CoP would then be 5.18 and the system performance would exceed Annex 22 system 2 by 1.4% and the DX system by 4.3%.

3. CONCLUSIONS

In this project we have sought to meet the objective of an energy efficient and environmentally friendly superstore, utilising an innovative design that allows chilled water fan coil air conditioning units and chilled water-cooled refrigeration systems to operate on a common water loop. This system will not only meet the store's refrigeration and air conditioning requirements, it will do so with efficiency savings unobtainable from either conventional direct expansion (DX) or secondary technologies. Energy savings are conservatively estimated to match the Annex 22 predictions but with scope for considerable further improvement as the product is optimised, and with capital costs comparable to conventional remote systems.

The system runs on natural refrigerants, eliminating the need for ozone depleting or global warming synthetic refrigerants. The use of water-cooled condensers allows integrated refrigeration within the display cases in a self-contained configuration, thus greatly reducing refrigerant charge and leakage potential. The heat from the refrigeration equipment is removed by the circulating chilled water, and can be recovered to provide all the store's heating provided the cooling absorbed electrical power exceeds the heating requirement for the store.

We believe that we have achieved our objective to develop and prove the water-cooled refrigeration system concept to the stage where commercial demonstration can commence. Examples of all items of equipment that would be required for a supermarket installation have been tested. This trial version of the system has been analysed, refined and optimised in order to minimise energy consumption. The results are entirely consistent with the computer modelling carried out in earlier studies. In conclusion, this project has achieved a system design suitable for commercial demonstration prior to wider market adoption.

REFERENCES

1. EN441 part 4, 1994.
2. Castle T. P., Green R.H. "A supermarket refrigeration and heating system using hydrocarbon heat pumps and an ammonia chiller", IEA Annex 22 Workshop Proceedings, December 1997.
3. Stene J. "Guidelines for Design and Operation of Compression Heat Pump, Air Conditioning and Refrigerating Systems with Natural Working Fluids", Final Report from Annex 22 of the IEA Heat Pump Programme, December 1998.

Appendix 1: ICWL Schematic