



THE INSTITUTE OF REFRIGERATION

Improving the Energy Efficiency of Food Refrigeration Operations

by

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Abstract

In June 2006, a UK Government Department for Environment, Food and Rural Affairs (defra) funded project to “identify, develop and stimulate the development and application of more energy efficient refrigeration technologies and business practices for use throughout the food chain whilst not compromising food safety and quality” started. The project is a collaboration between 4 top University research groups, an industrial steering group and hundreds of stakeholders from the food and refrigeration industries. This paper brings

together, for the first time, the important current findings of this project.

The research programme has concentrated on three topics: mapping of energy use; identifying new technologies and feasibility studies on promising technologies.

In the mapping exercise we have identified and ranked the top 10 food refrigeration operations in terms of the potential to achieve the greatest total reduction in energy usage. We have identified the large energy savings that could be achieved with current knowledge and the barriers to their uptake. Clear gaps have also

been identified in 'real' energy data and in current knowledge in areas of technology, equipment, management, maintenance and overall understanding. We have critically reviewed all the 'new/alternative' refrigeration technologies in terms of their potential to save energy in a food refrigeration operation and their probable development timescale before they are likely to enter commercial use.

Finally, in silico studies have resulted in a powerful tool to optimise the energy consumption of a total 'food refrigeration' process. This is being used to direct further experimental studies, provide case histories and identify further research needs.

Introduction

The food manufacturing industry uses chilling and freezing processes as a means of preserving foods. Transportation and retail distribution uses further energy to maintain the foods at the desired temperatures. These are important steps in optimising the safety, quality and shelf life of foods for the consumer. With the rising concern over climate change, global warming and the recent sharp increases in energy costs there is increasing pressure to make significant reductions in carbon emissions.

In 2005 defra's Research Priorities Group identified the need to develop more energy efficient technologies for use throughout the food chain whilst not compromising food safety and quality. Research proposals were encouraged to meet these needs.

After a successful bidding process, a project was set up which brought together four partners with substantial strengths and experiences in different areas. The University of Bristol's Food Refrigeration and Process Engineering Research Centre (FRPERC) is the main centre of Food Refrigeration research within the UK. Brunel University's Energy and Built Environment Research Group's (EBERC) principal areas of activity are in the areas of thermal systems and their control. London South Bank University's (LSBU) research group has been notable in developing dynamic modelling of refrigeration systems, high efficiency refrigeration heat transfer and system optimisation techniques. The University of Sunderland's (US) specific role was to concentrate on research into business practices and how the application of these would improve the energy efficiency of food

refrigeration processes.

At the start of the project a Project Steering Group (PSG) was established with industrial representatives invited by defra, a defra project officer and representatives from each partner organisation. In addition, a large stakeholders group was set up input data into and disseminate data from the project.

The research programme was set up to concentrate on three topics:

1. Mapping of energy use.
2. Identifying new technologies and business practices.
3. Feasibility studies on promising technologies and business practices.

The topics were addressed broadly in sequence.

Mapping of Energy Use

Worldwide it is estimated that 40% of food requires refrigeration and 15% of the electricity consumed is used for refrigeration [1]. In the UK, 11% of electricity is consumed by the food industry [2]. However, detailed estimates of what proportion of this is used for refrigeration processes are less clear and often contradictory. Efforts to determine how much energy is used in each sector of the food industry for refrigeration are often hampered by the apparent lack of measured data and limited availability of process throughput data [3].

Identification of top ten

At the start of the project there was a general impression that there was a wealth of published and unpublished data on energy consumption of food refrigeration processes. The mapping exercise was therefore planned to start off with a 'broad brush' survey of published and readily available data from collaborating organisations, with the aim being to:

- a) Input values into the first two rows of cells in Table 1.
- b) Gather data on the average temperature of foods at the point of input and exit from the various processes and
- c) Use these data to calculate the total energy change in the food (row 3) and the overall efficiency of the process (row 4).
- d) Calculate the potential to reduce refrigeration energy in each process (row 5).

In temperature maintenance operations e.g. storage, transport, retail, etc. the actual would be compared with a target 'optimal' insulation

	Chilling	Freezing	Thawing Tempering	Secondary cooling	Chilled Storage	Frozen Storage	Transport	Retail	Catering
Energy used									
Through-put									
Energy change in food									
Efficiency									
Energy that could be saved									

Table 1. Energy efficiency matrix for food refrigeration processes.

situation. As part of the initial 'broad brush' approach, there was also the aim to break down the data in terms of commodity group using the same procedure as already described.

However, it rapidly became apparent that there were extremely few real data based on measured values of energy consumption in commercial or industrial food refrigeration systems. Many of the different, widely quoted, data on the energy used by different sectors, when systematically traced back to their sources, were based on the same initial data.

The differences in values quoted were due to the different assumptions made when scaling up the initial data to the whole UK situation. In the

few cases where the energy consumption of a specific refrigeration operation had been measured, almost none had corresponding data on the throughput of food through the process and the temperature change achieved.

A further substantial commitment in terms of time and effort devoted to searches, contacts with members of the steering and stakeholder groups and individual factory visits just confirmed the initial impression. However, to progress the project, the available data were analysed to come up with a 'best estimate of the top ten food refrigeration processes ranked in terms of their potential for total energy saving', Table 2. The sources behind the assumptions made to derive the top ten are detailed in [4].

	Sector	Energy	Saving		
		'000 t CO ₂ /y	GWh/y	%	GWh/y
1	Retail display	3100-6800	5800-12700	30-50	6300
2	Catering – kitchen refrigeration	2100	4000	30-50	2000
3	Transport	1200	4800	20-25	1200
4	Cold storage – generic	500	900	20-40	360
5	Blast chilling – (hot) ready meals, pies	20-330	309-610	20-30	180
6	Blast freezing – (hot) potato products	120-220	220-420	20-30	130
7	Milk cooling – raw milk on farm	50-170	100-320	20-30	100
8	Dairy processing – milk/cheese	130	250	20-30	80
9	Potato storage – bulk raw potatoes	80-100	140-190	~30	60
10	Primary chilling – meat carcasses	60-80	110-140	20-30	40

Table 2. Best estimate of the top ten food refrigeration processes ranked in terms of their potential for total energy saving.

Although frustrated by the lack of reliable scientific data behind the top ten it was strongly felt that the ranking of the processes identified was correct and that the substantial effort that would be required to fully confirm this could not be justified. Effort was therefore targeted to obtain further information on the top four processes and carry out a more detailed exercise on the primary chilling operations.

Retail

Investigations have been carried out of the electrical energy consumption of 2,570 retail food stores covering the whole range of retail food outlets from convenience stores to hypermarkets [5]. This has shown that a wide range of variability exists in the electrical energy intensity of these stores even within the same store category and the same retail food chain. The annual electrical energy consumption of 640 convenience stores of sales area between 80 m² and 280 m² ranges from around 700 kWh/m² to 2,900 kWh/m². As the sales area increases from 5,000 to 10,000 m² the average electrical energy consumption reduces from around 870 to around 660 kWh/m².

However, the energy consumption of the refrigeration systems, cabinets and stores, was not directly measured. It is believed that in hypermarkets 25-30% of the total energy is used for refrigeration, rising to over 60% for food dominant convenience stores. For the smaller

size food dominant stores, if the electrical energy intensity of the stores whose intensity is above average is reduced to the average by retrofit measures, annual energy savings of the order of 10% (310 GWh) can be achieved.

Although there are few data on the performance of individual cabinets in supermarkets, data were collected in laboratory tests on 208 cabinets [6]. This showed large differences in the performance of cabinets (Figure 1). Substantial differences in energy consumed were found between similar cabinets, which shows that by careful selection of cabinets large energy savings can be achieved.

Reducing energy consumption in a chilled multi-deck cabinet is substantially different to reducing it in a frozen well cabinet. Improvements have been made in insulation, fans and energy efficient lighting but only 10% of the heat load on a chilled multi-deck comes from these sources compared with 30% on the frozen well. Research efforts are concentrating on minimising infiltration through the open front of multi-deck chill cabinets, by the optimisation of air curtains and airflows, since this is the source of 80% of the heat load. In frozen well cabinets reducing heat radiation onto the surface of the food, accounting for over 40% of the heat load, is a major challenge.

Catering

Refrigerated Commercial Service Cabinets

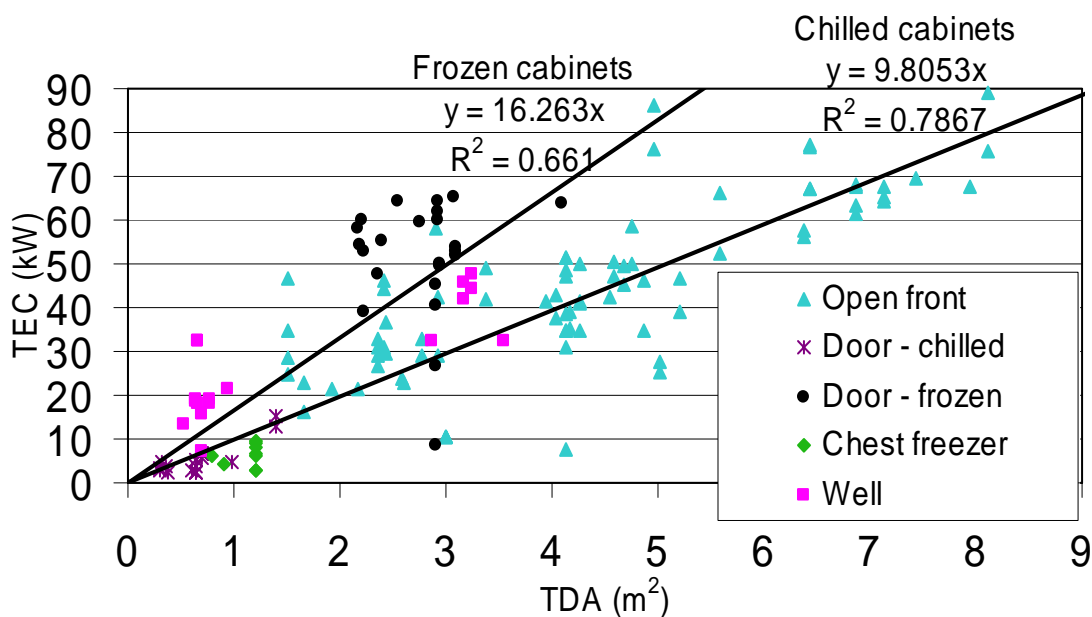


Figure 1. Relationship between TDA (total display area) and TEC (total power consumed) for 280 chilled and frozen cabinets.

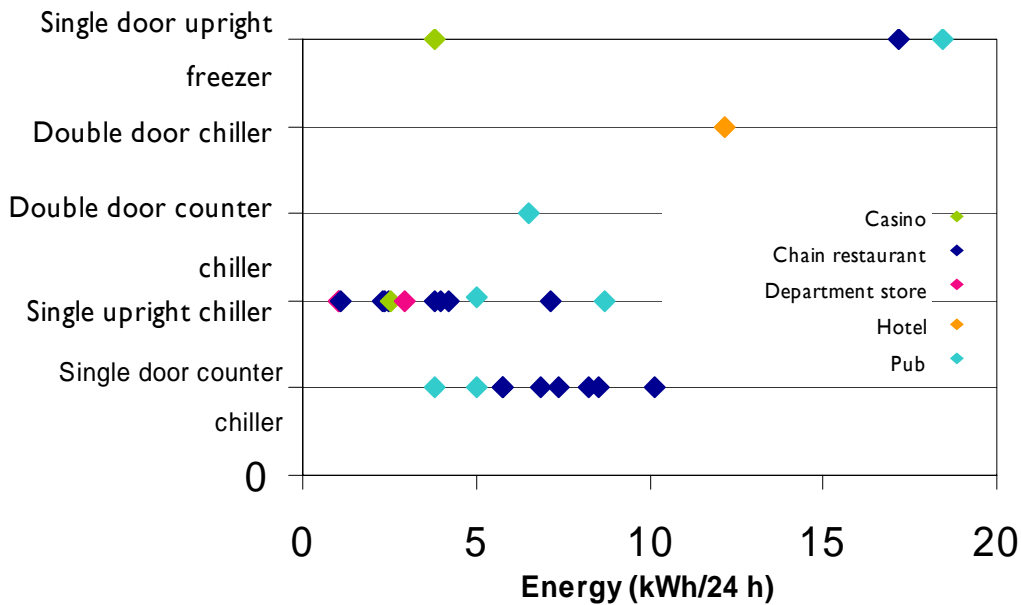


Figure 2. Energy consumed by different types of CSCs in different types of catering establishments.

(CSCs) are used to store food and/or drink in commercial catering facilities. There are approximately 500,000 units in use in the UK [7]. The vast majority of the cabinets sold are integral cabinets (refrigeration system on board the unit). The majority of the market is for chilled or frozen upright cabinets with one or two doors or under counter units with up to four doors. The average energy consumption for chilled cabinets is 2,920 kWh per year and for frozen is 5,475 kWh per year [7].

The limited published data on energy consumption of CSCs in use are shown in Figure 2. Although each cabinet type is of similar size and therefore can be directly

compared in terms of functionality there is a large difference in energy consumed by each CSC type.

Simply replacing current CSC cabinets by the best available, in terms of energy consumption, would save 1,000 GWh per year.

Studies carried out in a small catering operation showed that an upright frozen storage cabinet consumed over 40% of the energy used in refrigeration. Two small cost-effective changes, i.e. cleaning the condensing coil and resetting the thermostat, produced energy reductions of 8 and 11% respectively.

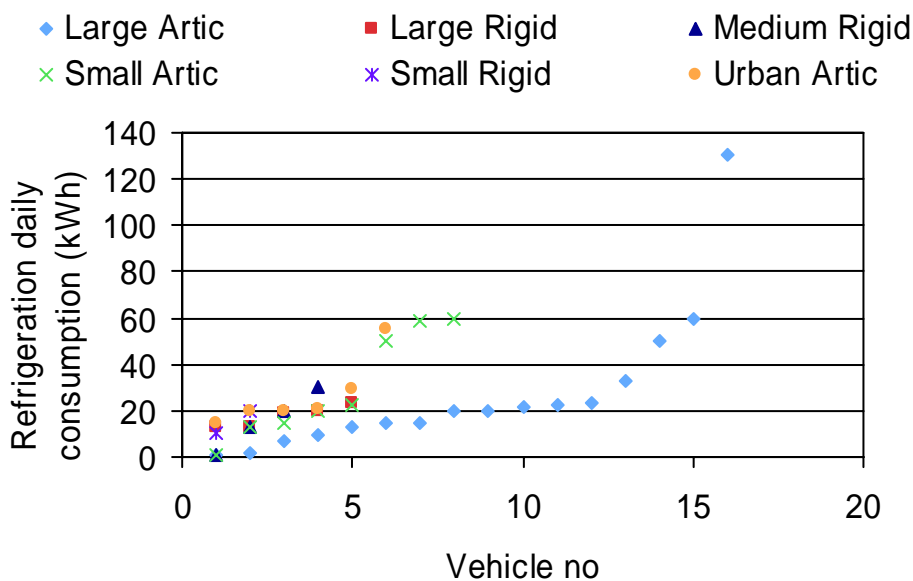


Figure 3. Energy consumption of refrigeration systems of transport vehicles.

Transport

As part of their input into the project Brunel University have carried out a review of food transport refrigeration [8]. This concluded that the Coefficient of Performance (COP) of transport refrigeration systems was low, ranging from 0.5 to 1.75 and that up to 40% of diesel consumed during transportation is used by the refrigeration system. However, the conclusions had to be based on theoretical and derived data due to the lack of any experimentally measured data on fuel consumption by refrigeration systems in commercial use.

Only one example has been located where the amount of fuel consumed by the refrigeration systems in different commercial refrigerated vehicles in the UK was actually measured [9]. The data, transformed into kWh consumed on the day of measurement, are shown in Figure 3. Again it is clear that there is a wide range of energies used, both between and within categories, and research is required to determine the reasons for the range and transfer the knowledge obtained to the industry.

Cold stores

Limited published data on energy consumption in cold stores have been found [10; 11; 12; 13] and little is UK based. FRPERC has therefore carried out a comprehensive study of three large cold store complexes in the UK. The actual performances of the UK cold stores per cubic and square metre are shown in Table 3. Predicted savings in energy assuming that door protection was improved, pedestrian doors fitted, liquid pressure amplification pumps fitted, defrosts optimised, suction liquid heat exchangers fitted and other minor issues corrected would result in reductions in energy of 23% in cold store 1, 5% in cold store 2 and 39% in cold store 3. If cold store 2 were fitted with an evaporative condenser the savings would increase to 38%.

Refrigeration plant	kWh/yr	kWh/yr/m ³	kWh/yr/m ²
Cold store 1	710,335	57.3	458.3
Cold store 2	652,573	71.1	710.6
Cold store 3	1,138,178	57.9	463.1

Table 3. Energy consumed by each cold store.

Primary chilling

Primary chilling is the first and most important

stage of the cold chain for a refrigerated food. The rate of temperature reduction often determines the subsequent safety and quality of the food. In primary cooling systems, the majority of the total heat load should be the product load since the purpose of a primary chilling system is to extract this load. The extraction of this energy from the food must be carried out in the most energy efficient manner.

The product heat load is dependent on the initial temperature of the product (at harvest or slaughter), the final temperature to which the product is required to be cooled prior to storage, and the mass of the product that is being cooled. In some raw products (fruits and vegetables) heat from respiration is also part of the heat load but this has been assumed to be insignificant for the purposes of this study.

The aim of this work was to:

1. Identify the major primary chilling energy requirements in the UK.
2. Calculate or make a best estimate of their efficiency.
3. Determine which chilling processes had the highest energy saving potential.

To achieve these aims all available data on the annual volume (tonnes) of each of the major raw food materials produced in the UK were collated. The annual amount of thermal energy that has to be removed post harvest or slaughter to cool the food to its recommended storage temperature, i.e. the temperature at which it enters the chill chain, was then calculated. Available data on the amount of energy used in existing chilling systems were then used to estimate the current efficiency of chilling systems and the processes with the greatest energy saving potential identified [14].

Overall, milk is chilled in substantially larger tonnages than any other single primary food material or material category in the UK. Throughput of potatoes, which are the next largest single primary food, is less than 40% of the milk tonnage. However, this is still substantially larger than any other raw material category.

The energy required to cool each of the raw food materials was calculated using the overall weight of annual UK production multiplied by the enthalpy change required to reduce the temperature post harvest/slaughter to its recommended storage temperature. In the UK,

milk is the raw material that requires the most cooling with an estimated energy value at least 2.5 times more than all the other major materials added together and over 4.5 times more than all types of meat combined. In addition to milk and meat the primary chilling of vegetables, especially potatoes, requires the extraction of substantial quantities of heat.

To be able to calculate the energy efficiency of current primary chilling processes data are required on the measured energy consumption of industrial systems for a known throughput of the raw material being chilled. The authors have been able to locate very few publications that contain both measured energy and throughput data. However, five publications have been located that provide some relevant data on milk [15; 16], potatoes [17] and meat [18; 19] which are three of the key primary raw materials in terms of a high primary chilling energy requirement.

There are a number of stages in quantifying the potential to save energy in different primary chilling operations. The first stage is a simple technology transfer exercise in which the most energy efficient current industrial process is identified.

With milk and carcass meat, data exist which allow a first attempt at calculating the energy reduction potential of a simple technology transfer exercise (Figure 4).

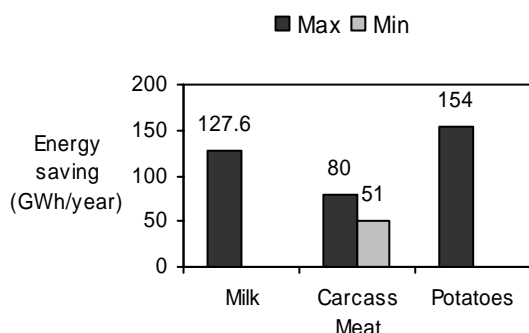


Figure 4. Energy saving potential with existing technology transfer.

A second stage of the process to identify potential to save energy is to see if a simple technology transfer between sectors would be beneficial. The cooling of a liquid product such as milk is a very different process to that of

cooling solids such as potatoes and meat carcasses. However, meat carcasses and potatoes are both cooled in air based systems so should it be possible to make potato cooling as efficient as the best of the measured carcass cooling plants i.e. improve the efficiency from 0.313 to 1.725, which would result in a potential annual saving of 154 GWh.

Identifying New Technologies and Management Systems

New/alternative technologies

Brunel University have carried out a review of the potential of new/alternative refrigeration technologies to reduce energy consumption in food refrigeration [20]. The review has mainly concentrated on the following seven systems: Trigeration, Air Cycle, Sorption – Adsorption Systems, Thermoelectric, Stirling Cycle, Thermoacoustic and Magnetic refrigeration. Ground heat exchangers for heating and cooling and ejector refrigeration were also considered. Characteristics and potential applications of these systems are summarised in Table 4.

The majority of trigeneration systems in the food industry are large plants in the MW range in food factories where bespoke ammonia plant are linked to gas turbines, or internal combustion engines. More recently, the application of trigeneration has been extended to supermarkets with a very small number of installations in the USA, the UK and Japan.

Air cycles also generate high air temperatures, typically of over 200°C, that can be used in combination with the low temperatures to integrate cooking and refrigeration processes. In the food sector air cycle technology can be applied to rapid chilling and/or freezing (including air blast, tunnel, spiral, fluidised bed and rotary tumble equipment); for refrigerated transport (trucks, containers, rail freight, ships, air cargo); and for integrated rapid heating and cooling (cook-chill-freeze or hot water/steam raising and refrigeration).

The application of sorption-adsorption systems in the food sector are likely to be in areas where waste heat is available to drive the adsorption system. Such applications can be found in food factories and transport refrigeration.

Current applications of thermoelectric refrigeration in the food sector include: hotel

room (mini-bar) refrigerators; refrigerators for mobile homes, trucks and cars; portable picnic coolers; wine coolers; beverage can coolers; drinking water coolers. Other potential future applications include domestic and commercial refrigerators and freezers, and mobile refrigeration and cooling systems.

Stirling cycles have been evaluated experimentally for application to domestic and portable refrigerators and freezers as well as vending cold beverages. Values of COP between 2 and 3 have been reported for temperatures around 0°C, and values around 1 for temperatures approaching -40°C.

It is likely that the potential market for

Thermoacoustic refrigeration for food applications will initially be in the low capacity equipment size, such as domestic and commercial refrigerators, freezers and cabinets.

In food applications, magnetic refrigeration has the potential for use across the whole refrigeration temperature range, down to cryogenic temperatures but it is anticipated that the first commercial applications will be for low capacity stationary and mobile refrigeration system.

It is expected that many of these novel refrigeration technologies will find niche application in food refrigeration operations in the future. For example, one commercial

Technology	State of development	Cooling/ refriger. Capacity of presently available or R&D systems	Efficiency/ COP of presently available or R&D systems	Current/Potential application area(s)
Trigeneration	Large capacity bespoke systems available. Smaller capacity integrated systems at R&D stage	12 kW to MW	Overall system efficiency 65-90%. Refrig. system COP: 0.3 at -50°C 0.5 at -12°C	Food processing; cold storage; food retail.
Air Cycle	Bespoke systems available	11 kW to 700 kW	0.4-0.7	Food processing; refrigerated transport
Sorption-Adsorption	Available for cooling applications > 0°C. Systems for refrigeration applications at R&D stage.	35 kW to MW	0.4-0.7	Food processing; cold storage; retail; refrigerated transport
Ejector	Bespoke steam ejector systems available	Few kW to 60 MW	Up to 0.3	Food processing; refrigerated transport
Stirling	Small capacity 'Free' piston systems available. Larger systems at R&D stage	15 W – 300 W	1.0 – 3.0	Domestic refrigerators, vending machines, refrigerated cabinets
Thermoelectric	Low cost low efficiency systems available.	Few Watts to 20 kW	0.6 at 0°C	Hotel room mini bar refrigerators, refrigerators for trucks, recreational vehicles; portable coolers; beverage can coolers
Thermoacoustic	R&D stage. Predicted commercialisation: 5-10 years.	Few watts to KW capacity	Up to 1.0	Domestic and commercial refrigerators, freezers and cabinets
Magnetic	R&D stage. Predicted commercialisation 10 plus years from now	Up to 540 W	1.8 at room temperature	Low capacity stationary and mobile refrigeration systems

Table 4. Characteristics and applications of new/alternative refrigeration technologies.

company 'Camfridge' hope to have a commercial magnetic water cooler available in 3 years. Currently, it is difficult to identify any that will make a step reduction in food refrigeration energy consumption.

Promising Technologies

In silico studies

Development of model

A purely experimental investigation of the energy saving potential of different technologies and food management systems was prohibitive in terms of time and available resources. A key part of the project has therefore been to use an 'in silico' approach together with experimental validation to provide a tool to optimise existing systems and quantify alternatives.

Cleland [21] in his 1990 book on the analysis, design and simulation of food refrigeration processes states "No accurate model of a complete food refrigeration system is possible unless both the refrigeration users and mechanical plant are considered simultaneously in the model." There are many publications of the modelling of the individual components. Models are available on the temperature response of foods during refrigeration processes including tempering [22], crust freezing [23], transportation [24] and retail display [25]. On the refrigeration system side, models include cold-space thermal design issues, [26, 27]; steady-state and transient refrigeration [28, 29]; refrigerator – cold space systems, [30, 31]; etc. In 1990 Cleland had only located one model that met his criteria [32]. Since then integrated limited models have been produced for food transport systems [33] and food storage systems [34]. The aim of the current work was to produce a much more comprehensive model.

London South Bank University have developed a computer based, dynamic simulation software of a D-X type, air-to-air, vapour compression refrigerator combined with cold-space and ambient weather model, with the working title of 'VCRmodel'. This is the type of system most commonly found in batch chilling and freezing systems in the food industry and is also found in many chilled and frozen storage rooms.

The software simulates a refrigeration system consisting of up to six single stage compressors, an air-cooling evaporator, a dry-air cooled condenser, thermostatic expansion valve,

associated refrigeration pipe-lines and control systems. The simulation software also includes physical models of condenser and evaporator fans, their drive-motors, and an electric defrost system and its control. The simulated control system choices include; cold-space thermostat options; defrost switching options; evaporator and condenser fan-motor speed control options; compressor staging and speed control. The software also allows the user to select outdoor ambient weather conditions by choosing a location and time of year for the simulation. The user is also able to design the structure of the cold-space and the time of day when the food-product is loaded.

The interactive software allows data to be entered into the model which calculates the time dependent transient responses of a refrigerator and cold-space to variations in outdoor and indoor air temperatures and humidity. Transmission and infiltration heat loads through the structure and doors, internal loads from lighting, people and food-product are all taken into account. The food-product load is calculated using a food thermal model 'FoodTemp' [22, 23] developed by FRPERC that takes as input the air temperature and flow determined by the VCRmodel. These data are used to determine the amount of heat removed from food in the refrigerated space and the rate of cooling in the food. The amount of heat released by the food is returned as input to the VCRmodel, so that the total energy consumed at each stage of the process can be determined. The total food/refrigeration model is shown schematically in Figure 5.

Input screens in the model allow for data for specific refrigerator system components to be defined in detail. These include screens for compressors, evaporator, condenser, expansion valve, control options and so on. Another screen is used to enter details of the food being processed, in terms of its basic composition, and its configuration and starting conditions. From the compositional data a module within FoodTemp calculates the thermal properties of the food over the temperature range of interest, for use in the calculation of cooling rates and heat load described above. Other screens allow the cold-space to be designed and the ambient weather to be set. Product loading schedule is defined in the main run screen, which gives continuous graphical output for selected data. There is also facility to

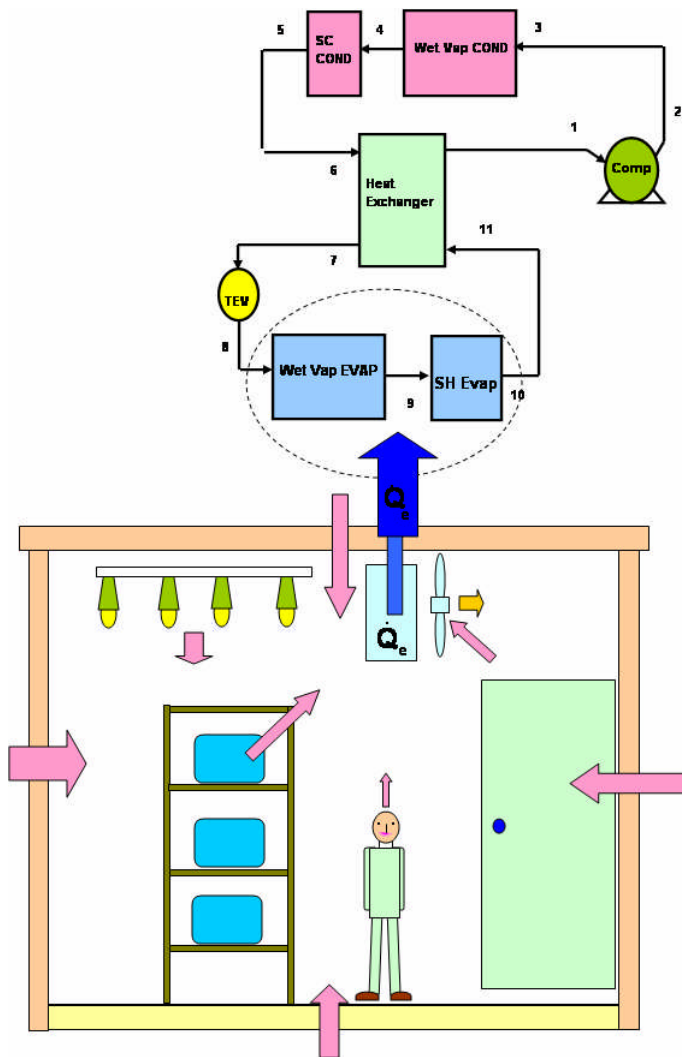


Figure 5. Schematic of total food/refrigeration system model

interactively increase or decrease compressor and fan speeds whilst the simulation is in progress. The user can simulate the performance, for example, of a whole Cold Store system; for a day, a week, a month, however long they wish.

Commercial verification

The model is a very powerful tool with substantial potential to optimise energy consumption in existing systems and aid the design of promising technologies. However, before that potential could be realised it is important to fully verify the predictions of the model against commercial reality. During the mapping exercise it became very clear that comprehensive reliable data on a food refrigeration process in the detail required to verify the model did not exist.

A study was therefore undertaken to gather all the data required to run the model and also

experimentally measure all the parameters required within a refrigeration system and the food being cooled to fully verify the model. This of course included the total energy consumed by the system and the total amount of product being cooled from a known initial to a known final temperature during the process. The system consisted of a single compressor, vertical wall mounted condenser unit and a push-through rack chilling tunnel (Foster Refrigerator) with an evaporator with two vertical banks each of three axial electric motor/fan units. The system is used for cooling cooked pie fillings in trays on wheeled trolleys from 75°C to below 5°C. The blast chiller was switched on at 09.08 and rapidly reached its control conditions (Figure 6). Since two loads of cooked filling were required to completely fill a trolley, the trolley did not enter the tunnel until 12.46 and shortly after a defrost occurred followed by another 4 hours later. The product was removed from the tunnel at 18.41. The power data were integrated to produce data on the energy used throughout the process and over different stages.

The model was then run after inputting all of the component design data and the measured parameters, and the predictions in terms of food temperatures and energy used compared with the measured values.

The average measured and predicted pie filling temperature during the chilling operation are shown in Figure 6. It can be seen that the predicted rate of temperature fall closely follows the measured data. The maximum difference between the predicted and measured mean centre tray temperature at any time is 5.9°C, the average difference is 2.3°C. The measured and predicted energy consumptions over 15 minute intervals are shown in Figure 7. The difference between the predicted (58.9 kWh) and measured (64 kWh) overall energy consumption is 5.1 kWh, an 8 % difference. The base load i.e. the average power used without any food product was predicted to be 5.1 kW and the measured value 5.6 kW, a 9 % difference.

It is exciting that the initial validation has produced such small errors in the prediction of food temperatures and energy consumption. During the verification process information gained from the comprehensive monitoring exercise were available to refine the model.

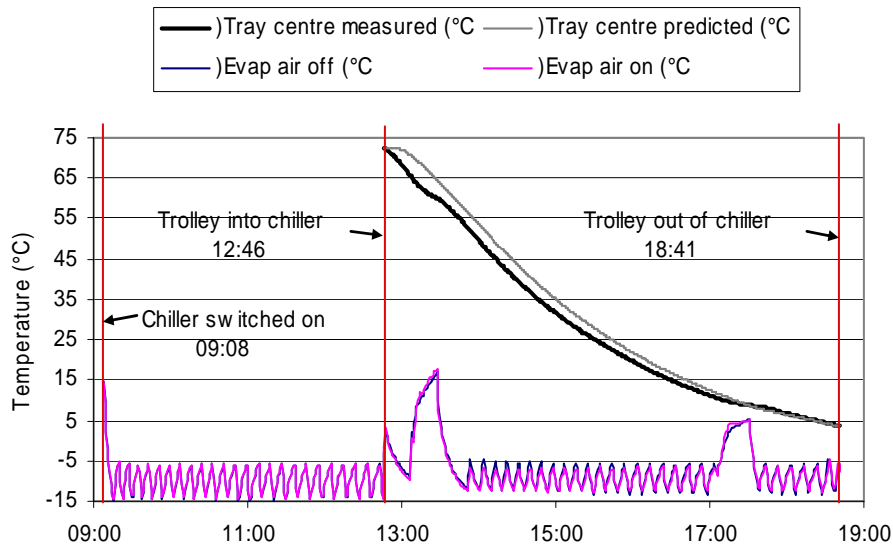


Figure 6. Plot of pie filling temperatures cooled in Foster blast chiller (centre of trays 1 to 6) and chiller temperatures (air on and air off).

These data would not normally be available and a considerable amount of time and effort is now being invested in further verification and development to produce a robust, fully tested model and to identify its limits of application.

Conclusions

The top ten food refrigeration processes, in terms of the potential to reduce energy consumed, have been identified and ranked. On the best available data the energy saving potential in the top five operations retail, catering, transport, storage and primary chilling lies between 4300 and 8500 GWh/y. However, the mapping exercise revealed a dearth of reliable measured data on the energy consumption of refrigeration systems within the total food cold chain. In the few cases where

energy data had been collected it was difficult to correlate with food throughput and heat removed from the food to obtain true efficiency data. Without real data on energy consumption and useful heat extracted it is impossible to benchmark existing operations, provide sensible targets or quantify the true effect of energy saving technologies.

It is clear that maintenance of food refrigeration systems will reduce energy consumption. Repairing door seals and door curtains, ensuring that doors can be closed and cleaning condensers produce significant reductions in energy consumption. It was disappointing that a survey carried out as part of this project has shown that regular maintenance of food refrigeration plant is not part of the operation

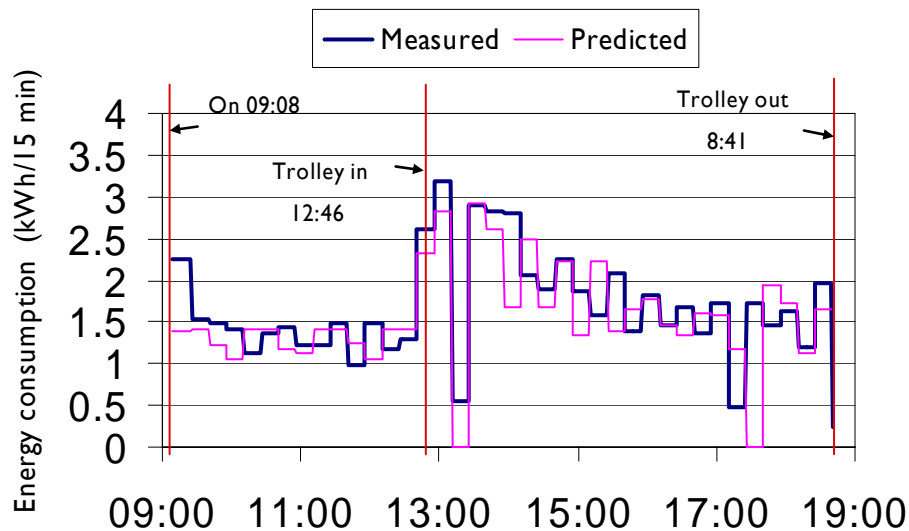


Figure 7. Predicted and measured energy consumption over 15 minute intervals.

of many plants. Refrigeration maintenance is reactive in most of the plants visited.

In the retail environment the majority of the refrigeration energy is consumed in chilled and frozen retail display cabinets. Laboratory trials have revealed large, up to 6 fold, differences in the energy consumption of frozen food display cabinets of similar display areas. In chilled retail display, which accounts for a larger share of the market similar large differences, up to 5 fold, were measured. A substantial energy saving can therefore be achieved by simply informing and encouraging retailers to replace energy inefficient cabinets by the best currently available.

▪ Research studies are then required to quantify the key energy saving features of the best cabinets and starting from this point develop substantially improved designs.

Making substantial reductions in the energy consumption of refrigeration systems in catering environment is difficult because of the very large number of small refrigeration systems involved. Caterers need to be informed about the energy efficient devices that are on the market when they are replacing systems. However, it is difficult on a cost saving basis to justify replacing an existing device. The payback period is likely to be in excess of 7 years. The limited real data obtained on the performance of devices in practical use show that the way a refrigeration device is used in catering substantially effects its energy consumption.

▪ Research studies are therefore required to identify the operational factors that substantially effect energy use in catering refrigeration systems.

In large cold storage sites the cost of refrigeration energy makes up a much higher proportion of operational costs than in other food refrigeration processes. In the studies at three sites it was shown that energy could be substantially reduced if door protection was improved, pedestrian doors fitted, liquid pressure amplification pumps fitted, defrosts optimised, suction liquid heat exchangers fitted and other minor issues corrected. The most cost effective changes were however, site specific and no generic energy saving process was identified.

In terms of the heat energy to be extracted

during the primary chilling process the six most important food categories in rank order are milk (532 GWh/y), meat (114 GWh/y), potatoes (59 GWh/y), other vegetables (36 GWh/y), fish (6.5 GWh/y) and fruit (5.9 GWh/y). From the few published data that are available the energy efficiency (useful heat extracted from material/ measured electrical energy used) varies from 0.138 to 5.337. Cooling of milk is far more efficient than that of the next two most important categories, meat and potatoes. Using the best of existing technologies it is estimated that 154 GWh could be saved per year in potato cooling, 128 GWh in milk cooling and between 51 GWh and 80 GWh in the cooling of carcass meat. Savings in other commodity areas are likely to be more than an order of magnitude less.

A comprehensive review of new/alternative systems has revealed several with energy saving potential if applied to food refrigeration. However, none appear to be likely to produce a step change reduction in refrigeration energy consumption within the next decade.

A composite dynamic model, which incorporates a refrigeration module with a food-cooling module, has been developed. The refrigeration module simulates the performance of a direct expansion refrigeration system with a single stage compressor, single evaporator and air-cooled condenser. The food module handles products in different configurations with temperature dependent thermal properties. In an initial verification against data from a commercial system the maximum difference between the predicted and measured mean centre tray temperature at any time is 5.9°C, the average difference was 2.3°C. The difference between the predicted (58.9 kWh) and measured (64 kWh) overall energy consumption is 5.1 kWh, an 8 % difference. The authors feel that the model has exceptional potential as a tool to aid the:

1. Energy optimisation of existing food refrigeration systems,
2. Design of new energy efficient food refrigeration systems, and
3. Identification of the energy saving potential of totally new systems and refrigeration approaches.

Some of the specific questions we hope to answer with it in the very near future are:

1. What is the most energy efficient method of

cooling a food?

2. Is there an optimum food configuration (thickness) from an energy viewpoint?
3. What is the optimum defrost strategy?
4. Is one big or several small compressors more energy efficient?
5. Is there an optimum evaporator/condenser face area?
6. What savings can be made by changing evaporator fan speeds or using different fan control strategy?

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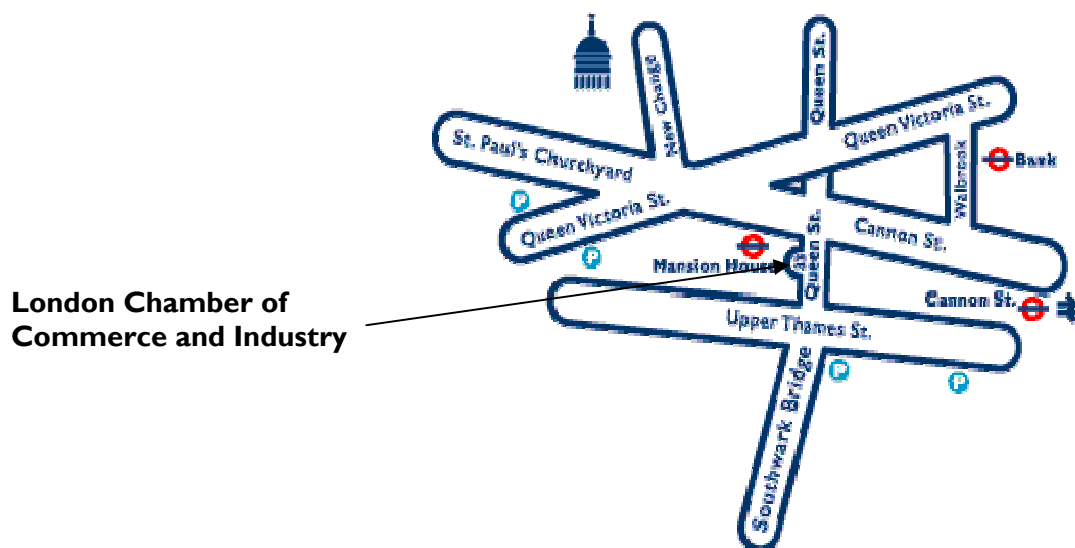
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