Mr Stephen James *is the Director of the Food Refrigeration and Process Engineering Research Centre (**FRPERC**) at the University of Bristol. He was a founder member of the Meat Research Institute in 1967 and carried out research on the refrigeration of meat then all foods until the Institute's closure in 1990 and the formation of FRPERC. His 300 publications cover all aspects of food refrigeration from primary chilling through freezing, thawing, tempering, storage, transport, retail display to consumer handling and the performance of domestic refrigerators.*

He has been an associate member of the IIR for many years, serving on Commission C2. FRPERC organized a very successful symposium "Rapid Cooling – Above and below zero" for the IIR in 2001 (for the proceedings CD-ROM, contact: www.iifiir.org). FRPERC carries out a very wide range of research and industrial consultancy on the total cold chain for food and increasingly other products. In addition it specializes in air cycle refrigeration, thermal decontamination systems and microwave processing. Full details of its activities can be found on ***www.frperc.bris.ac.uk***

Developments in domestic refrigeration and consumer attitudes

by
Stephen J. James
Food Refrigeration and Process Engineering Research Centre (FRPERC),
University of Bristol, UK
Steve.james@bristol.ac.uk

INTRODUCTION

Refrigerators and freezers are the two main refrigerated appliances in domestic use. Worldwide, there are about 1 billion domestic refrigerators and freezers.[1] However, the sales of other small domestic refrigeration systems such as stand-alone ice cream makers, ice makers, cooled water dispensers and drink coolers are increasing. With the exception of air conditioning, the prime use of domestic refrigeration systems is for food storage.

The past decades have seen a considerable increase in legislation defining maximum temperatures during the production, distribution and retailing of chilled food. However, as soon as the food is purchased by the consumer, it is outside of any of these legislative requirements. Increasingly, food poisoning incidents have been found to be due to mishandling of food in the home with insufficient refrigeration or cooling being the most frequent factor causing disease. Out of the 1562 cases of food poisoning reported in the UK during 1986 to 1988, 970 (62%) were caused in the home. Consumer handling of products may not be as intended or envisaged by the manufacturer. Many chilled products are purchased on the basis of the 'fresh image', but then frozen at home.

After a chilled or frozen product is removed from a retail display cabinet, it is outside a refrigerated environment whilst it is carried around the store and then transported home for further storage. In the home it may be left in ambient conditions or stored in the refrigerator/freezer until required. There are few published data on the performance of domestic refrigeration and the consumers' attitudes to chilled food and their handling procedures in the home.

I. SCIENTIFIC STUDIES

The following is a brief review of some of the scientific studies on domestic refrigeration that have been carried out in recent years to illustrate the wide range of topics. Most cover the refrigeration systems and their use or ability to refrigerate food. A number cover temperature performance and consumer handling/attitudes.

Refrigeration systems

Radermacher and Kim[2] published a review of domestic refrigeration in 1996. This comprehensively covers the history and development of domestic refrigerators and freezers from a refrigeration engineering view. In the final section they state that 'recent environmental concerns led to a considerable boost to efforts emphasising two aspects (i) environmentally safe fluids and (ii) reduced energy consumption'. In general, the same two aspects have continued to dominate research since that time.

The technology of using a heat pump for air conditioning and domestic hot water heating has been investigated for many years. Ji et al[3] investigated a novel air-conditioning system that could achieve the multi-functions with improved energy performance. Their results show that by incorporating a water heater in the outdoor unit of a split-type air-conditioner so that space cooling and water heating can take place simultaneously, the energy performance can be raised considerably.

Inan et al.[4] used an X-ray system to study the transient behaviour of a domestic refrigerator. The investigations used a two-door upright freezer with a volume of 435 litres, which had an automatic defrost feature. Real time X-ray video images of the refrigeration circuit were taken during the pull-down and during normal control cycles. X-ray images were taken of the dryer, capillary exit, evaporator inlet, and accumulator regions. By matching the video images and temperature data, the flow regimes, charge inventory, accumulator functioning, and changes of sub cooling degree at dryer inlet were explained. They also identified possible flow induced noise mechanisms.

Noise control in domestic refrigerators was also the subject of a review paper by Suzuki.[5] He reported that it was difficult to realize sufficient noise reduction by means of active noise control in the low-frequency region. Although it is possible to reduce noise from an isolated compressor, it was far more difficult when the compressor was incorporated in a refrigerator. Noise reduction was achieved utilizing an acoustic isolation panel with a heat-exhaust opening for heat evaporation. The heat-exhaust opening contained an evaluation microphone for radiation noise. The noise level was reduced using sound insulation and absorption structure in the machine enclosure. The application of active control of exhaust sound proved highly effective for control of broadband sounds, which had hitherto been difficult to realize.

The use of hydrocarbons is probably the largest current research topic in the domestic refrigeration area. Hammad and Alsaad[6] looked at replacing R12 with four ratios of propane, butane and isobutane. The parameters investigated were the evaporator capacity, the compressor power, the coefficient of performance (COP) and the cooling rate characteristics. Their work showed that a mixture with 50% propane, 38.3% butane and 11.7% isobutane was the most suitable of the hydrocarbon mixtures investigated. When this hydrocarbon mixture was used the evaporator temperature reached -16°C with a COP of 3.7 compared with 3.6 for the traditional R12 refrigerant at the same temperatures. The refrigerator worked satisfactorily with the proposed alternative refrigerant without the need for any modification or adjustment. Akash and Said[7] found that liquefied petroleum gas (LPG) compared well with R12 in a domestic refrigerator. The COP was higher for all mass charges at evaporator temperatures lower than –15°C. Overall, it was found that a mass charge of 80 g of LPG was best and cooling capacities could be three- to fourfold higher than those for R12. Tashtoush et al.[8] found that a butane/propane/R134a mixture provide excellent performance parameters compared to R12. There was also no need to change the lubricating oil. Similarly Jung et al.[9] reported that a propane/isobutene mixture seems to be an appropriate long-term candidate to replace R12 and R134a from the viewpoint of energy conservation requiring minimal changes in the existing refrigerators.

Finally Bansal and Martin[10] have looked at the performance of domestic refrigerators with cooling systems, which do not use any refrigerant that damages the ozone layer. They looked at thermoelectric and absorption refrigeration in comparison with standard vapour compression. Three refrigerators of similar capacity (about 50 l) were compared for their usage in the hotel industry in view of their energy efficiency, noise produced and cost (owning as well as running). It was found that the vapour-compression refrigerator consumed the least energy, was least costly but was the noisiest. The absorption refrigerator was the quietest of the three but was the least energy efficient and had the most expensive overall lifetime costs. The thermoelectric refrigerator was the most expensive to buy, nearly as noisy as the vapour-compression refrigerator, but was a little more energy efficient than the absorption refrigerator.

Food temperatures and consumer use

It is well known that unprotected chilled food will warm up during transportation to the home. Survey results[11] showed that consumers took on average 43 minutes to bring meat, fish or dairy items home from the shops and place them in a refrigerator. Although insulated bags and boxes are widely sold, only a small percentage (12.7%) used them to transport some of their food home. The vast majority (87.3%) of people did not use any means of protecting food from temperature gains during transportation. Some of the meat product temperatures in samples placed in a car boot rose to around 30°C during the 1-hour car journey, whilst most of the samples placed in a insulated box cooled during the car journey except for a few at the top of the box which remained at their initial temperature. The temperature of frozen products (starting at –25°C) placed in both the cold box and ambient rose during

the 1-hour journey. Temperatures of chickens and meat pies placed in ambient reached temperatures approaching 10°C. Frozen meat products, in the cold box kept below -10°C for the period of the journey.

In the past decade there have been at least eight surveys of temperatures in domestic refrigerators. The results are very similar (*Table 1*) with overall mean temperatures ranging from 4.5 to 6.6°C and maximum temperatures from 11 to 14°C. These results are very worrying since they imply that the average temperature of at least 50% of domestic refrigerators is above 4.5°C. When we look at the percentage of temperatures measured that were above set points the results are even more worrying. In the last French study[12], 80% of the temperatures were above 5°C and in the Greek work[13] 50% above 9°C.

Table 1. Temperatures measured in 8 surveys of domestic refrigerators in homes

Reference	Country	Number of samples	Measurement	T_{min}	T_{mean}	T_{max}	% >x°C
Flynn et al.[14]	Northern Ireland	150	Thermometer (3 levels: T, M, B)	0.8	6.5	12.6	71%>5°C
James and Evans[15]	UK	252	Data logger (3 levels: T, M, B)	0.9	6.0	11.4	23%>7°C
Victoria[16]	France	102	Thermometer (3 levels: T, M, B)			14	70%>6°C
Lezenne Coulander[17]	The Netherlands	125	Thermometer				70%>5°C
O'Brien[18]	New Zealand	50	Thermometer (2 levels: T, B)	0	4.9	11	60%>4°C
Sergelidis et al.[13]	Greece	136	Thermometer				50%>9°C
Laguerre et al.[12]	France	119	Data logger (3 levels: T, M, B)	0.9	6.6	11.4	80%>5°C
Jackson[19]	Northern Ireland	30	Data logger (1 level M)	-5	4.5	13.0	53%>5°C

In Jackson's ongoing investigations[19], only 17% operated below 5°C for the entire week of monitoring.

In the Laguerre et al[12] study, a two-dimensional analysis (crossed table) was used in order to verify the relationship between factors (characteristics of refrigerator, use conditions and characteristics of participants) and between factor and overall temperature. It was found that there is no direct relationship between these, particularly in terms of temperature settings and refrigerator temperatures. Seven percent of refrigerators with high temperature settings still have a low temperature (<2.5°C) while 6% of refrigerators that have low temperature settings, still had a high temperature (>10°C). Analysis of the refrigerators located near heat sources did not enable conclusions to be drawn concerning this effect on temperature since the overall temperature varies from low to high. However, no built-in refrigerators had temperatures under 2.5°C.

The investigation showed that statistically there is no relationship between temperatures measured using a thermometer at a given moment and using a data logger over a 7-day period. An increasing number of refrigerators are sold with a single point temperature display; however, these authors stated that 'the temperature measured using a thermometer does not represent the true operating conditions of the refrigerator'.

Although temperatures in domestic refrigerators are high they do not appear to directly relate to food poisoning. Parry et al[20] related the occurrence of sporadic salmonella food poisoning with food consumption and food handling practices, opportunities for cross contamination and refrigerator temperature control, in 99 households in South East Wales (UK) in 1997-1998. Using univariate analyses, the persons affected were significantly more likely than control respondents to have purchased free-range eggs in the preceding week, and more likely than control households to have handled frozen whole chicken in the previous week, and to handle raw chicken portions at least weekly. In multivariate analysis, only consumption of raw eggs and handling free-range eggs were

significant risk factors, independent of the age structure of the family and of the season. Refrigerator temperature control was not a significant factor.

In general it also appears that consumers do not worry about food storage temperatures. Consumers in the UK surveys[11] were asked at what temperature they tried to operate their refrigerator. Nearly all participants were unable to name actual temperatures and gave answers based on the method they used to set the temperature dial. A large number of people (32.8%) set their refrigerators according to the weather, setting the refrigerator to a lower temperature (higher setting) in the summer. It was interesting to note that although 38 participants had a thermometer in their refrigerator, only 30 actually used the information to set their refrigerator temperature.

Marrakchi et al[21] looked at French women's attitude to home hygiene. A phone-call survey was performed from November 22 to 28, 2000, among 500 women, 18 years of age or more. The women were selected according to usual poll techniques (quotas according to age, social condition, housing, region, etc.), and their answers were overweighed for mothers with infants. The results were very revealing. Spontaneously, the word "hygiene" called to mind cleanness (46%), or housekeeping (20%), but food hygiene or body hygiene was mentioned by only 3% of women. The three most spontaneously mentioned places at home, as requiring strict hygiene, were the kitchen (83%), bathroom (78%), and restroom (67%). The refrigerator was spontaneously mentioned by only 4% of the women surveyed, but was rated as 9 to 10, on the risk scale, by 82% of the same women. The three factors perceived by over 30% of women as facilitating bacterial growth were humidity, lack of hygiene, and dust. The bad conservation of food was mentioned by only 8% of women, this ranked the same as the presence of pets. The words Listeria (or listeriosis), Salmonella (or salmonellosis) and Staphylococcus were in the mind of only 22%, 18%, and 13% of the women respectively. Poor home hygiene is more and more frequently mentioned in the media, during epidemics. However, in France the general population's knowledge is still poor and requires information and education.

Poor consumer knowledge of food handling is not confined to Europe. Jay et al.[22] carried out a telephone food safety survey of 1203 randomly selected Australian households. All respondents were aged 18 years or over, were the main grocery buyers of the household, purchased red meat products at least once a month, and regularly prepared food in the household. There were significant gaps observed in the food safety knowledge of many respondents surveyed. Forty percent of respondents thawed raw meat at room temperature, 85% allowed cooked foods to cool at room temperature before refrigerating, and almost 70% of respondents were not aware of the correct refrigeration temperature for storage of perishable food. Almost 25% of respondents failed to identify that washing hands before handling food and during food preparation was important in reducing the risk of cross-contamination and possible foodborne illness. The findings raise important concerns about domestic food handling practices in Australian homes and the level of food safety knowledge in the community generally.

II. COMMERCIAL DEVELOPMENTS

Most of the recent developments in domestic refrigeration have been driven by tighter energy legislation. In the EU, most countries implemented EC Directive 96/57/EC on energy efficiency requirements for household electric refrigerators, freezers and combinations thereof, by the end of 1999. Household refrigeration appliances were already required to carry EC energy labels under earlier, related EC Directives (92/75/EEC on the indication by labelling and standard product information of the consumption of energy and other resources by household appliances, as applied by 94/2/EC on energy labelling of household electric refrigerators, freezers and their combinations). The effect of these new regulations will be to remove most of the appliances labelled D to G, while appliances labelled A to C will be allowed. The exception is chest freezers where appliances labelled A to E will be allowed.

Domestic refrigeration appliances use about 24% of the electricity consumed by all domestic electrical appliances, equalling lighting. There is considerable technical potential to improve the energy efficiency of the appliances in use by removing the least efficient products from the market, encouraging take-up by consumers of the more efficient products on sale and by encouraging manufacturers to introduce more efficient products to the market. The European Commission expect, by setting minimum efficiency standards, to help to achieve a 15% reduction in the total EC electricity consumed by refrigeration appliances in 1992.

LG Electronics, have developed an energy efficient free piston linear compressor for a household refrigerator. This linear compressor demonstrated excellent energy efficiency and reduced the energy consumption of refrigerators by more than 20%.

The claimed advantages of the linear compressor are as follows:

- Since there is no crankshaft the friction loss and wear problems in the compressor can be reduced.
- The valve systems of the linear compressor are more efficient than that of the reciprocating compressor because of the reduction of heat transfer and flow resistance loss.
- The linear motor is more efficient than a current induction motor.
- The control method of the linear compressor is simple and efficient.

The manufacturers claim that it is possible to use the linear compressor instead of a reciprocating compressor without changing any other components except compressor itself. Just changing from a reciprocating compressor to the linear compressor, the energy consumption of a 0.6 m^3 side-by-side refrigerator decreased by >20%. The noise level of the refrigerator with the linear compressor is similar to that of the current refrigerator.

Niche markets

As already mentioned, temperature control is not normally a sales point for domestic refrigerators. However, there are niche markets where good temperature control can establish a market. An example is the Kimchi refrigerator.

Kimchi refrigerator

Kimchi is the most popular side dish in Korea. Kimchi is a fermented product that relies on lactic acid production at low temperatures to ensure proper ripening and preservation of the product. It is processed with a seasoning mixture consisting mainly of red pepper powder, garlic, ginger, green onion, radish, etc. Very good temperature control is required to allow consumers to enjoy fresh Kimchi for 2 to 3 months. Kimchi contains 3 to 5% salt and its structure deteriorates if kept below –2°C. If kept at temperatures above +1.5°C its storage life is substantially reduced.

Special Kimchi refrigerators are now produced that maintain average product temperatures in the range –1 to –0.5°C with a maximum temperature of 1.5°C within the storage compartment. Currently the refrigerators cost 50% more than standard systems and are only sold in Korea. Despite these restrictions the market in 2003 is estimated to rise to 1.5 million appliances worth 1.3 billion US dollars. Currently, 30% of Korean homes own both a Kimchi and a standard refrigerator. The main manufacturers, LG, Samsung and Mando, provide premium, chest and drawer type versions.

Boy's toys

Another growth market in the domestic refrigeration sector is the gadget or 'boy's toys' area. Increasingly in the developed world, well-off individuals are looking for ways of spending their money. The purchase of designer gadgets is rising.

In the domestic refrigeration market, the gadgets are typically stylish wine coolers, icemakers, ice cream makers and individual refrigerators for drink cans. Since the market is not price-sensitive, alternative refrigeration systems such as Peltier ones are often used.

Figure 1. **Wine chiller and Peltier refrigerator for drink cans**

III. THOUGHTS ON THE FUTURE

Domestic refrigerators and freezers have essentially changed very little in the past 40 or more years. They are basically insulated boxes refrigerated using a standard vapour-compression system. The prime attribute governing purchase is the cost per unit storage volume. Increased efficiency has become a sales feature in the developed world and many countries are introducing legislation to further improve efficiency. This will apply more pressure to make appliances more efficient without scarifying internal product space.

A growing, but still small, percentage of the market in the developed world is for larger designer appliances with many features. Often the design of these appliances is 'retro', harping back to the style of those produced in the USA in the 1950s and 1960s. Features usually include ice and crush ice dispensers, can and bottle cooling and storage sections often accessible through a small door within the door, many door compartments and separate compartments for different foods. Improved control of food temperatures is not a sales point.

Will there be a breakthrough in domestic refrigeration?

1. Will there be refrigerators that keep foods at the optimum temperatures for quality and safety?

The technology exists and many white goods manufacturers are willing to make it happen. Increased demand for ice cold drinks may act as the catalyst. It will be ironic if the consumer need for cold fizzy drinks results in refrigerators that keep high-risk chilled foods at the correct temperature.

2. Will the vapour-compression system be replaced?

There are a number of alternatives to the conventional vapour-compression cycle. They include: adsorption systems, thermoelectric/Peltier, thermionic, vortex tubes, air cycle, magnetic cooling, Stirling cycle, Malone refrigeration, acoustic cooling, pulse tube and water cycle. Domestic refrigerators using adsorption refrigeration have had a limited market for many years. Peltier systems are well established in the transportable and boys' toys markets. However, neither appears poised to break into the mass market.

Of all the technologies, thermionic cooling has the potential to revolutionise the domestic refrigeration market. Cool Chips Ltd., the development leaders, claim:

- 30% plus saving in average annual energy cost when compared to the best Embraco 115 V compressor;
- 53% saving in production cost for the cooling equipment within a 0.4 m^3 refrigerator/freezer, which meets US DOE 2001 energy regulations;
- the thermionic refrigerator will be quieter, more spacious and lighter due to the lack of a compressor;
- the thermionic refrigerator will not cycle as much, thanks to better temperature control.

However, I have yet to see, or be provided with reliable evidence that any thermionic chip has ever produced sensible amounts of cooling. We may therefore have to wait a considerable length of time before there is a real step forward in domestic refrigeration.

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