Food chilling and freezing technologies:

Potential for energy saving

By

Judith Evans

Produced by:

Food Refrigeration and Process Engineering Research Centre (FRPERC),

University of Bristol, Churchill Building, Langford, North Somerset,

BS40 5DU, UK

Tel: ++44 (0)117 928 9239 Fax: ++44 (0)117 928 9314

e-mail: frperc-bris@bristol.ac.uk Web: http://www.frperc.bris.ac.uk

Contents

1. Refrigeration systems in the food industry

Refrigeration system choice is a vital part of selecting an efficient freezing or chilling system for long-term use. The size of the refrigeration system will vary according to the amount of heat that needs to be removed and ideally the heat load will be minimized. In cooling or freezing heat will be removed from the product whereas in storage, transport and retail the only heat loads ought to be from transmission across structures, infiltration through doors and openings and from lighting, defrosts and people and machinery.

In chilling or freezing the rate of heat removal from products will determine the size of the plant. Smaller, thin product will cool and release heat more quickly than large, thicker products. In all cases the rate of heat release will not be constant. The maximum rate of heat release will occur in the initial stages of cooling when the temperature difference between the surface of the product and the refrigerating medium is highest. As the surface temperature of the food approaches that of the refrigerating medium the rate of heat release will be very small. Cooling in the centre of foods is effectively controlled by the rate of conduction from the centre to the surface. Increasing the air flow (or heat transfer coefficient) over the product has minimal benefits once the surface temperature is close to the cooling fluid temperature.

It is essential in all refrigerated rooms that food is loaded correctly and does not impede air movement around the room and that air does not bypass the food. By correct loading and ensuring that air did not by-pass product in the room Odey (2006) found that for the same air temperature and freezing times that the fan power required to distribute the air over the food could be reduced by half. In another example from New Zealand, Edwards and Fleming (1978) showed that by optimising air flow and using 2 stage fans that the energy consumed during carton freeing of lamb could be reduced to a quarter of that used in conventional air blast freezing.

The most common refrigeration systems in operation in the food industry are based on direct expansion of a refrigerant (DX systems). In some sectors of the food industry pumped recirculation systems are common (e.g. in the cold storage industry). The refrigerant (most commonly ammonia) is contained in a large vessel termed a ‘surge drum’ and is pumped or fed by gravity to the evaporators. The efficiency of most refrigeration plant could be improved. Most estimates indicate that 15-30% reduction in energy usage would be achievable by optimising plant performance, better maintenance or replacing key components.

2. Process optimisation

The majority of short term energy savings are likely to be achieved through process optimisation and replacement of key components.

Equipment choice

The method used to chill or freeze a product can have a large effect on the overall energy efficiency. Information within this area is often limited as it is difficult to directly compare industrial processes. Data is occasionally available to compare overall production and energy consumption such as that presented in Ramirez et at (2006). This provides useful data for the meat industry in four European countries (UK, France, Germany and the Netherlands) to show that poultry production is more energy intensive than pork and beef and that energy use for meat processing varied between the four countries studied. However, it does not break down the data to enable any information to be extracted to identify why different processes should utilize more or less energy.

Chourot et al (2003) accepted that process information is difficult to obtain but stressed that to truly compare processes that detailed information is essential. The authors developed a model to compare freezing costs, which included product parameters, refrigeration system characteristics, and costs for operation as well as investment. Costs for freezing strawberries using mechanical, immersion freezing and cryomechanical freezing were compared. The results indicated that immersion freezing was the cheapest process and cryomechanical the most expensive.

Work by De Jong (1994) comparing air blast and plate freezing of beef cartons in New Zealand showed that the power consumed per carton of beef for plate freezing was lower than two alternative air blast freezing processes. This was corroborated by Visser (1996) who demonstrated that freezing times could be reduced from 47 to 18 hours and energy costs by 24% when plate freezing rather than air blast freezing meat (Figure 1). Cooper (1980) collated and compared the costs for a number of freezing operations. When freezing beef burgers the overall operating costs (investment, fixed costs and variable costs) to freeze using a spiral freezer was just over half that required for liquid nitrogen or carbon dioxide freezing. It is relatively difficult to directly compare the energy costs for the 3 systems as the energy costs for production of the cryogens should be taken into account and these vary considerably (a new cryogen plant may consume half the energy of an older less efficient one). Although operational costs for the liquid nitrogen and carbon-dioxide plants were more than the spiral freezer, if the costs of evaporative weight loss was taken into account the overall differences between operating costs between the 3 systems was considerably less (Figure 2).

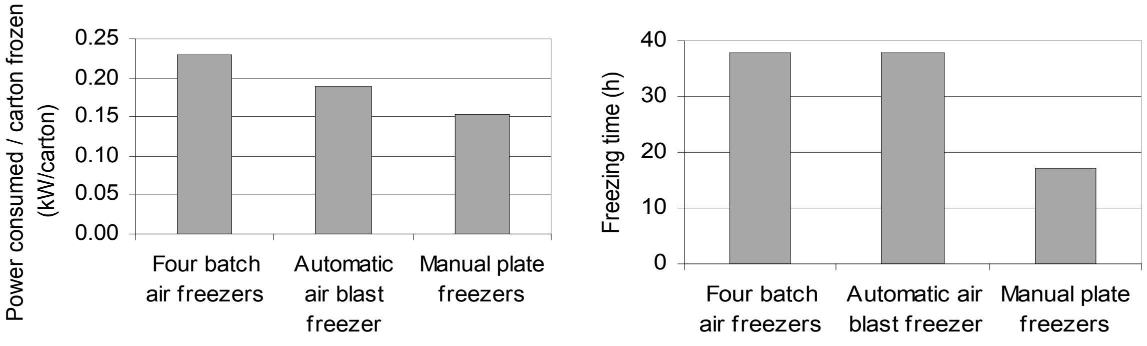

Figure 1. Energy required for freezing and freezing time for cartons of beef (from De Jong, 1994)

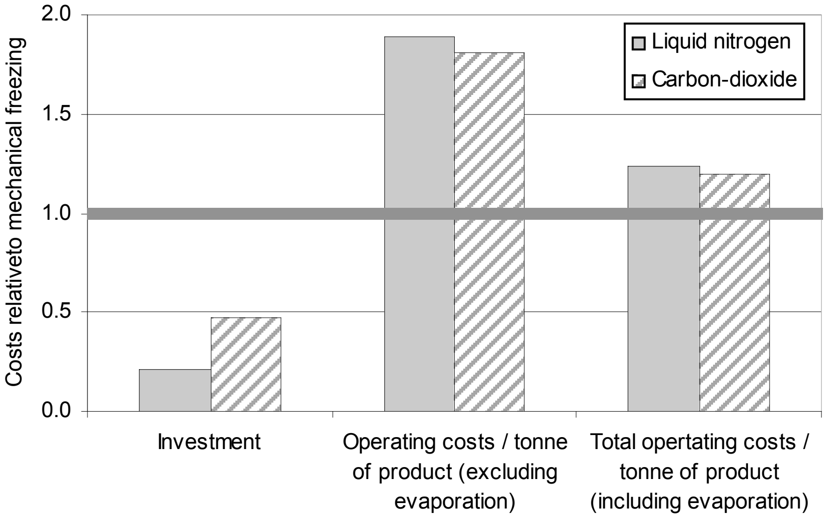

Figure 2. Costs Costs of freezing burgers in nitrogen and carbon-dioxide relative to mechanical freeing (from Cooper, 1980).

Work in Denmark by Pedersen (1979) compared the energy consumed in 5 different chilling methods for poultry. When only energy costs were considered counter current water chilling costs were one fifth of those for air chilling. However, once the costs of water and waste disposal were taken into account the water chiller was 50 times more than the air system (Figure 3).

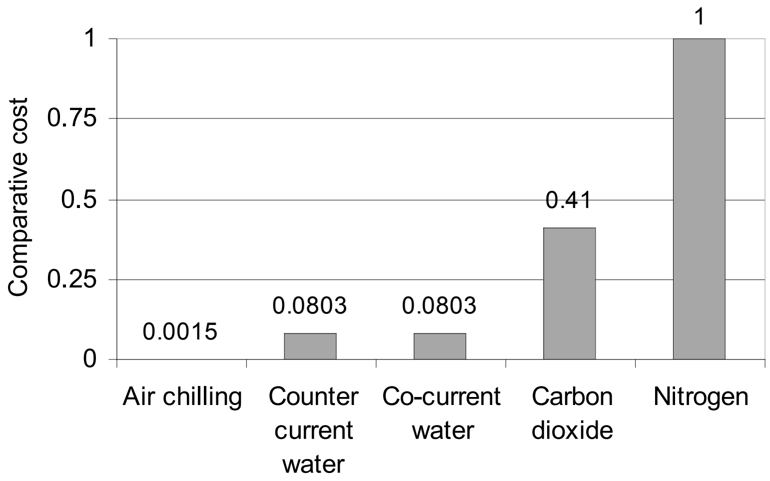

Figure 3. Comparative costs of chilling poultry (from Pedersen, 1979).

The use of localized air delivery systems to cool food directly was considered by Burfoot et al (2004). The system utilized localized air delivery systems consisting of air supply ducts located on each side of a conveyor. By using localized delivery systems savings of up to 26% were obtained when compared to operating the production area at 5°C. Savings of up to 32% were achieved compared to operating at 10°C. In addition the system was claimed to improve food safety and the conditions for workers.

Equipment operation

Many cold store operators utilize control strategies to save energy. This can involve control of evaporator fans, the refrigeration system or of temperatures inside the cold room. It is common for operators to switch off refrigeration systems during peak demand energy periods when energy is more expensive ('load shedding'). During load shedding the temperature within the room is allowed to rise slowly and is then it is reduced once the cost of the energy returns to a lower level.

Any reduction in the refrigeration system condensing temperature or rise in the evaporating temperature will save energy. In many instances temperatures (especially in frozen stores) are kept lower than necessary to provide a safety margin in case of plant failure. If any potential failure can be predicted by monitoring plant performance preventative maintenance can be carried out. Control systems can also be used to identify the optimal time to load shed, defrost and to run compressors (to minimize part load operation) to maintain the correct temperature whilst minimizing energy usage.

Most chilling or freezing processes are single stage systems where the air temperature and velocity remains constant throughout the chilling or freezing process (single stage system). An alternative is a two-stage system where the air temperature and/or air velocity are changed as some point in the process. This can be especially advantageous when chilling as a low initial temperature can be used to rapidly reduce the surface temperature to a value just above its freezing point. The air temperatures can then be raised to prevent surface freeing. When freezing product the air speed can be high in the initial stage to rapidly reduce surface product temperatures to close to the air temperature and can then be reduced in a second stage. Once the surface temperature of a large product is close to the air temperature conduction will be the major heat transfer mechanism and therefore high air velocities are no longer necessary. In addition lowering the air velocity will reduce the fan heat load on the room and reduce energy consumption.

Data presented by James and Bailey (1990) for a range of two-stage chilling systems for beef showed that chilling times to below 7°C could be achieved in under 18 hours and that weight loss was reduced by up to 1.37%. Likewise for pork James et al (1983) and Gigiel and James (1984) have shown that the initial peak heat load can be extracted from a carcass by a rapid initial chilling procedure followed by a slowed second stage. Weigh loss was reduced by half compared to controls. However, the energy consumed during the chilling process was never measured in the experiments so the relative energy efficiency of these two stage systems is not known.

Heat recovery

In several applications heating and cooling can be carried out simultaneously. By utilizing heating as a by-product of the cooling process this can increase the overall process efficiency. The temperature at which heat is rejected from the refrigeration cycle is the critical factor that defines how useful the heat can be to an end user. In most well designed direct expansion refrigeration systems the heat rejected from the system is not high enough to be especially economically useful. One exception to this is in cold stores where the compressor discharge gas is commonly used to heat pumped glycol under floor heaters to prevent the ground under the cold store freezing and damaging the store floor (‘commonly called ‘frost heave’). Another is the relatively low grade heat that can be reclaimed from the oil coolers of screw compressor where up to 60% of the compressor motor power can be absorbed in the oil. Systems have been developed that use heat from the compressor discharge or compressor oil coolers to pre-heat water in a boiler. Although these were traditionally considered uneconomic, with improved building insulation, the low grade heat available becomes more attractive. In an example presented by Das (2000) a combined heating and cooling system that provided under floor heating and pre boiler water heating to 35°C gave a pay back period of 2.5 years. Due to the increases in fuel costs the benefits of heat reclaim are becoming more apparent and systems for supermarkets and medium sized plant that allow heat to be reclaimed for water or space heating are now becoming available. In addition the use of bore water cooling has been shown to be an effective means of reducing condensing temperatures in locations where bore water is available.

In warmer countries the use of solar heat for cooling using either an absorption system or from photovoltaic cells has shown some potential for storage of vaccines and drugs. Smaller refrigerators have been shown to be able to viable use solar radiation when combined with other storage solutions such as eutectic ice packs to overcome storage times when solar radiation is not sufficient to provide all the cooling.

3. New/alternative refrigeration methods and systems

Ambient cooling

Although active cooling using refrigeration systems is the primary means of cooling food in the food industry it is possible in many instances to obtain some free cooling from ambient air. Cooked foods can be cooled by 20-30°C by blowing ambient air over the product whilst maintaining a relatively large temperature difference between the food and air. For example predictions carried out using a mathematical model similar to that described by Evans, Russell and James (1996) to chill a Bolognese sauce ready meal of 50 mm thickness from 80°C to 5°C in air at –5°C compared to ambient cooling at 20°C for 1 hour followed by active cooling at –5°C showed that the ambient treatment required 24 minutes longer than the direct chill. However, the ambient cooling treatment heat load was reduced by 49% (Figure 4). Assuming sufficient space is available for the ambient cooling the use of ambient cooling will reduce the amount of heat that needs to be extracted by the refrigeration system resulting in increased chiller throughputs.

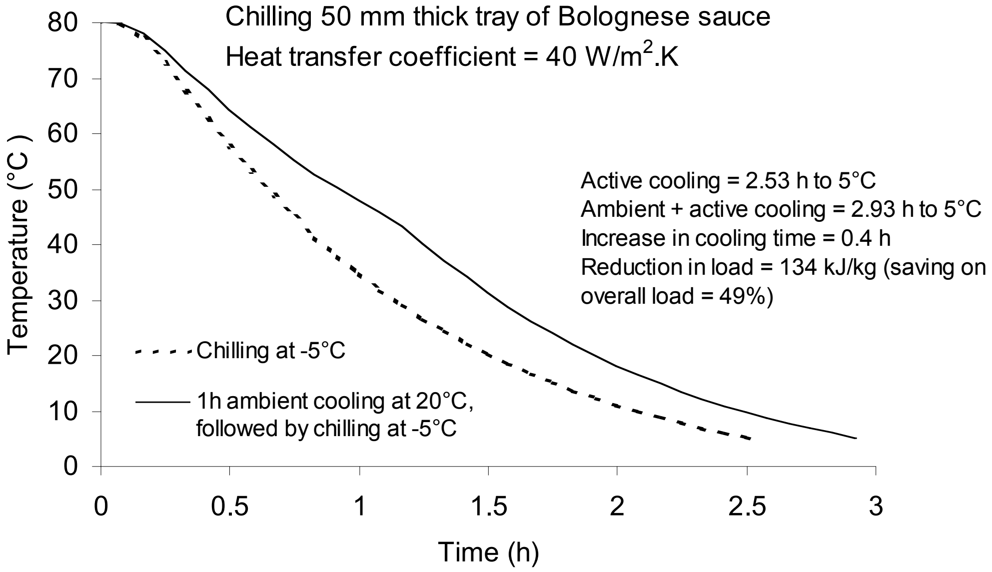

Figure 4. Effect of ambient cooling on 50 mm thick tray of Bolognese sauce.

Perfusion

Under EU legislation meat carcasses must be chilled to below 7°C before leaving the slaughterhouse. Typically this is done by passing cold air streams over the surface of an eviscerated carcass or side. Because the cooling medium is only acting on the outer surface, it can take many hours for the temperature at the centre of the carcass to drop below 7°C. In vascular perfusion chilling (VPC), a cold fluid is circulated through the intact vascular system theoretically offering significant reductions in cooling time. Reducing the time required to chill carcasses will have substantial benefits to the meat industry in terms of both quality and energy usage. Such a treatment is still in the development stage but systems not aimed to provide full chilling have been used in the USA and Australia to remove blood from carcasses and claim improved hygiene (Dikeman et al, 2003, Wang et al, 1995).

Hot boning

As described earlier most large food objects rely on conduction cooling once the surface approaches the temperature of the air passing over the object. In meat chilling the rate of heat loss from the carcass is considerably restrained by the thickness of the carcass. By boning and portioning the meat immediately post slaughter the chilling time can be reduced considerably. In addition there are benefits in terms of reduced evaporative weight loss, hygiene and increases in process throughputs (due to faster chilling times). However, the largest refrigeration energy saving aspect is the reduction in the total mass of ‘meat’ to be refrigerated. The bones and surplus fat within a beef carcass can make up to 30% of the total weight of the carcass. In a hot boning operation these can be disposed of immediately after boning and do not have to be refrigerated.

In developed countries the use of hot boning has had little commercial uptake. There has also been little work to investigate the potential energy savings although these are claimed to be substantial (Taylor, 1985).

Immersion cooling

Immersing food in a cold liquid can achieve high heat transfer coefficients (values up to 500 Wm-2K-1). However, in most food applications the foods must be wrapped to prevent transfer of the cooling medium into the food. In addition the food needs to be partitioned into suitable sized pieces that can be easily handled. For this reason immersion chilling fits exceptionally well with hot boning for meat carcasses. Work carried out by Brown et al (1988) on pork primals showed that weigh loss was reduced by 1.9% in immersion chilled samples compared to conventionally chilled samples. Chilling times were between 2.3 and 3.5 hours less than conventional treatments.

Although the faster chilling times for immersion chilled samples would indicate that there is potential to save energy this has not received any attention. Currently immersion chilling has had rather restricted uptake outside of technologies such as sous-vide and other catering applications where rapid chilling is essential.

Evaporative cooling

Evaporating water from the surface of foods has a cooling effect. However, water loss affects eating quality and ultimate sales value. Spraying a sacrificial layer of water onto the surface of the food can increase evaporative cooling whilst retaining yield. Evaporative cooling is relatively common in poultry chilling but had applications for other foods. Investigations have shown that spraying water in the first few after slaughter provided the greatest savings in weight loss (Gigiel, Brown and James, 1992). Potentially the faster cooling times can reduce energy usage, although this has again received little investigation.

Impingement

Impingement technology increases the surface heat transfer in air chilling and freezing systems (Newman, 2001; Sundsten et al., 2001; Everington, 2001). Impingement is the process of directing a jet or jets of fluid at a solid surface to effect a change. The very high velocity (20 – 30 ms^{-1}) impingement gas jets, 'breakup' the static surface boundary layer of gas that surrounds a food product. The resulting medium around the product is more turbulent and the heat exchange through this zone becomes much more effective (Figure 5). Impingement freezing is best suited for products with high surface area to weight ratios (e.g. burgers) or for product requiring crust freezing. Testing has shown that products with a thickness less than 20 mm freeze most effectively in an impingement heat transfer environment. When freezing products thicker than 20 mm, the benefits of impingement freezing can still be achieved; however, the surface heat transfer coefficients later in the freezing process should be reduced to balance the overall process efficiency.

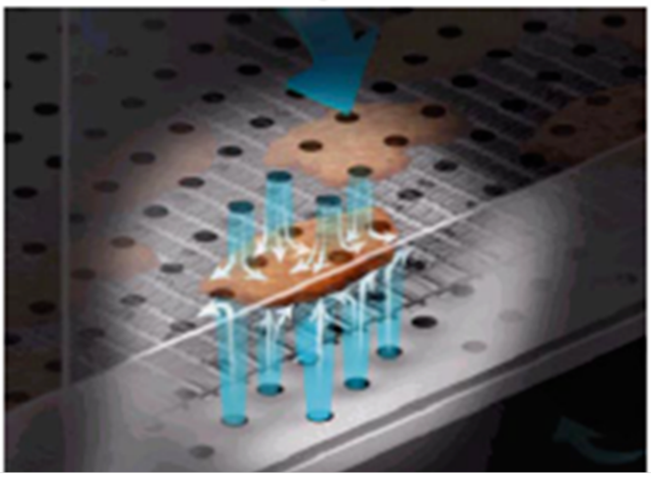

Figure 5. Impingement system (courtesy of Air Products).

Impingement freezing has substantial advantages in terms of freezing times. In trials carried out by Sundsten et al. (2001), the time required to freeze a 10 mm thick 80 g hamburger from 4°C to -18°C in a spiral freezer was 22 minutes whereas in an impingement freezer the time was 2 minutes 40 seconds. In addition dehydration was significantly higher for hamburgers frozen in the spiral freezer (1.2%) compared to the impingement freezer (0.4%).

Again no data is currently available on the energy saving potential of an impingement chilling or freezing system.

Heat pipes

The cooling of many cooked foods is limited by the rate at which heat can flow from the centre to the surface of the product. Investigations carried out by Ketteringham and James, (2000) showed the benefit of using high heat transfer devices including heat pipes, thermosyphons and solid metal rods to increase the cooling rate of hot foods. The use of high conductivity inserts reduced blast chilling times in mashed potato were cooled from 70°C to 10°C and 3°C by between 6% and 29% with heat pipes producing the greatest effect. The inserts had the potential to produce significant time and energy saving and improvements in food quality and safety.

4. References

Brown, T., Gigiel, A.J., Swain, M.V.L. and Higgins, J.A. 1988. Immersion chilling of hot-cut vacuum packed pork primals. Meat Science, 22 173-18.

Burfoot, D, Reavell, S, Wilkinson, D and Duke, N. Localised air delivery to reduce energy use in the food industry. Journal of Food Engineering 62 (2004) 23–28.

Chourot, J.M., Macchi, H., Fournaison, L. And Guilpart, J. Technical and economical model for the freezing cost comparison of immersion, cryomechanical and air blast freezing processes. Energy Conservation and management, 44, 559-571, 2003.

Cooper, T. J. R. Engineering Development Report, September 1980.

Das, F. (2000). Integrated heating and cooling in the food and beverage industry, Food and Beverage Industry, Newsletter No. 2, 2000.

De Jong, R. S. Plate freezing technology and economics applied to the meat industry. Proceedings IRHACE Technology Conference, Paper 11 (1994).

Dikeman, M.E., Hunt, M.C., Addis, P.B., Schoenbeck, H.J., Pullen, M., Katsanidis, E. and Yancey, E.J. (2003). Effects of postexsangination vascular infusion of cattle with a solution of saccharides, sodium chloride, and phosphates or with calcium chloride on quality and sensory traits of steaks and ground beef. Journal of Animal Science, 81, 156-166.

Edwards, B. F. and Fleming, A. K. The reduction of energy consumption due to fans in refrigerated areas. IIF-IIR Commission B2, Delft (The Netherlands), 1978-3.

Evans, J., Russell, S., James, S.J. Chilling of recipe dish meals to meet cook-chill guidelines. Int. J. Refrig., 19, p79-86.

Gigiel, A.J. and James, S.J. (1984). Electrical stimulation and ultra-rapid chilling of pork. Meat Sci. 11, 1-12.

Gigiel, A.J., Brown, T. and James, S.J. 1992. An introduction to immersion, spray and evaporative cooling and heating techniques. FRPERC workshop 'Cooking and Cooling Using Immersion Spray and Evaporative Techniques', Langford House, 28 January 1992.

James, S.J. and Bailey, C. (1990). Chilling of beef carcasses. In Chilled Foods - The State of the Art, Elsevier Science, 159-181.

James, S.J., Gigiel, A.J. and Hudson, W.R. (1983). The ultra rapid chilling of pork. Meat Sci. 8, 63-78.

Ketteringham, L., James, S. (2000). Use of high thermal conductivity inserts to improve the cooling of cooked foods. Journal of Food Engineering 45 (1), pp. 49-53.

Newman, M. (2001) Cryogenic impingement freezing utilizing atomized liquid nitrogen for the rapid freezing of food products. In Rapid Cooling of food, Meeting of IIR Commission C2, Bristol (UK).

Odey, M. (2006) Meat carton blast chilling/freezing cabinet performance improvements. Refrigeration Science and Technology Series 2006-1 118-124 (Proceedings IIR-IRHACE 2006 Conference, Auckland, NZ, 16-18 February, 2006; CD-Rom).

Pedersen, R. Advantages and disadvantages of various methods for chilling of poultry. Landbrugsministeriets Slagteri-og Konserveslaboratorium, Copenhagen, Denmark, Report No. 189, 1979.

Ramirez, C.A., Patel, M. and Blok, K. How much energy to process one pound on meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. Energy, 31 (2006), 2047-2063.

Sundsten, S., Andersson, A. and Tornberg, E. (2001). The effect of the freezing rate on the quality of hamburgers. In Rapid Cooling of Food, Meeting of IIR Commission C2, Bristol (UK).

Taylor, A.A. 1985. Optimal chilling & ES parameters for hot boning.. EEC Report of Working Party, Rome, 29-31st Oct. 1985. 'Accelerated Processing of Meat'. (Romita, A., Valin, C. & Taylor, A.A. eds), 3-19. Elsevier Applied Science Publishers Ltd.

Visser, K. (1996). The design and operation of large automatic plate freezers. Proceedings of the 19th International Congress of Refrigeration, Vol. 3a, 699-706, The Hague.

Wang, Y, McGinnis, D S, Segada, RR and Jones, S D M. (1995). Vascular infusion of beef carcasses effects on chilling efficiency and weight change. Food Research International, 28 (4), 425-430.