



REVIEW PAPER

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Effect of chilling, freezing and thawing on meat quality: a review

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Abstract

The specific effects of chilling and freezing are meat tenderness and texture, drip production, meat colour and appearance and odor and flavor. Low temperatures are required during carcass storage to prevent microbial spoilage. Cold shortening or cold toughening depends on the difference between hot carcass and environmental temperatures. Carcass size and degree of fatness are other factors that influence carcass temperature decline. Most concern during storage, distribution and retail display of meat and meat products is the minimum growth temperature for a microorganism. Domestic refrigeration and freezing significantly improves the texture, juiciness and aroma of meat. This paper discusses the effects of chilling and freezing on the quality of meat.

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Introduction

Temperature is one of the major factors affecting microbiological growth. Microbiological growth is described in terms of the lag phase and the generation time. Microorganisms have a maximum growth temperature above which growth no longer occurs. Above this temperature, one or more of the enzymes essential for growth are inactivated and the cell is considered to be heat-injured. However, in general, unless the temperature is raised to a point substantially above the maximum growth temperature then the injury is not lethal and growth will recommence as the temperature is reduced (James 2002). Red meat and poultry meat would be completely free of microorganisms, both pathogenic (food poisoning) and spoilage, when produced. There is little difference in the microbial spoilage of beef, lamb, pork and other meat derived from mammals (James and James 2009.; Varnam and Sutherland, 1995). Differences can be accounted by differences in initial bacteria levels, tissue composition and pH (Blixt and Borch 2002). The spoilage bacteria of meats stored in air under chill conditions include species of *Pseudomonas*, *Brochothrix* and *Acinetobacter/Moraxella*. Different species become important in the spoilage of vacuum packaged and modified atmosphere packaged meats. Of particular concern to human health are pathogens such as *Campylobacter* spp., *Salmonella* spp., pathogenic serotypes of *Escherichia coli*, *Clostridium perfringens*, *Clostridium botulinum*, *Yersinia enterocolitica*, *Listeria monocytogenes* and, to a lesser extent, *Staphylococcus aureus* and *Bacillus cereus*. The visual appearance of meat influences the consumers' willingness to buy it when raw. However, after cooking, the eating quality of meat is determined by tenderness, juiciness and flavour, as well as appearance (James and James 2009).

The prime purpose of a meat refrigeration process is to reduce the temperature of the meat to a value below which the rate of bacterial growth is either severely slowed (chilling) or stopped (freezing). A complete cold chain for meat or meat products will contain a number of temperature reduction

processes, viz. primary chilling, secondary chilling, freezing, together with other processes where no change in average meat temperature is required, i.e. chilled and frozen storage, transport, retail and domestic storage. It may also contain processes such as thawing, tempering and cooking, where a controlled temperature rise is planned, and others such as cutting, boning and mincing, which can result in an uncontrolled temperature rise. In processes where no change in meat temperature is required, the refrigeration system should be designed to minimise, if not eliminate from or into the surface of the meat. Almost all carcass-chilling systems for red meat carcasses, and many poultry chilling systems, rely on refrigerated air as the cooling medium. Most red meat systems use large insulated rooms with hanging rails for the meat carcasses or sides (James and James 2009).

As the temperature of an organism is reduced below that for optimum growth then the lag phase and generation time both increase. The minimum growth temperature can be considered to be the highest temperature at which either of the growth criteria, i.e., lag phase and generation time, becomes infinitely long. The minimum growth temperature is not only a function of the particular organism but also the type of food or growth media that is used for the incubation. Although some pathogens can grow at 0°C, or even slightly lower, from a practical point of view the risks to food safety are considerably reduced if meat is maintained below 5°C (James 2002).

In primary chilling, radiation is important only in the initial stages of the process in a system where the carcass is not surrounded by other carcasses. Again, in the initial stages of the secondary chilling of cooked meat products (e.g. pies, pasties, joints), radiant heat loss can be substantial if the products are surrounded by cold surfaces. Evaporation from a meat surface reduces yield and is not desirable in most meat refrigeration operations. In poultry chilling, evaporative (spray) chilling systems are sometimes used (James *et al.*, 2006).

Meat exhibits other particular quality advantages as a result of rapid cooling. In meat the pH starts to fall immediately after slaughter and protein denaturation begins. The result of this denaturation is a pink proteinaceous fluid, commonly called 'drip', often seen in pre-packaged joints. The rate of denaturation is directly related to temperature and it therefore follows that the faster the chilling rate the less the drip. Investigations using pork and beef muscles have shown that rapid rates of chilling can halve the amount of drip loss. A final quality and economic advantage of temperature control is a reduction in weight loss, which results in a higher yield of saleable material. Meat has a high water content and the rate of evaporation depends on the vapour pressure at the surface. Vapour pressure increases with temperature and thus any reduction in the surface temperature will reduce the rate of evaporation. The use of very rapid chilling systems for pork carcasses has been shown to reduce weight by at least 1% when compared with conventional systems (James 2002).

The cold chain

In general, as meat moves along the cold chain it becomes increasingly difficult to control and maintain its temperature. Temperatures of bulk packs of meat and meat products in large storerooms are far less sensitive to small heat inputs than single consumer packs in transport or open display cases. The cold chain links temperature changing operations, such as chilling, freezing, thawing, handling and cooking, and temperature maintenance operations, such as chilled and frozen storage, transportation and display.

Primary chilling/freezing

The first stage in the cold chain will therefore be a cooling operation to reduce the temperature of the meat to a value that limits microbiological and quality changes. If the meat is to be distributed in a chilled form then this value will be above the initial freezing point and in the range -1 to $+15^{\circ}\text{C}$. In many countries the legal limit is $+7^{\circ}\text{C}$. If a frozen food is required then the value will typically be between -12 and -30°C .

Secondary processing

The meat that is processed after its initial primary chilling (or freezing operation) is likely to gain heat (rise in temperature). This rise can range from a few degrees in a packing operation to 100s in cooking. Industrial cooking processes cannot be guaranteed to eliminate all pathogenic organisms and if cooling rates are slow microbial spores that survive the cooking process will germinate and grow. To maintain product quality it is often important to remove this added heat. Systems that produce a rapid reduction in the temperature of the meat will retard microbial growth and consequently extend shelf life (James 2002).

Storage and transport

After the temperature of the meat has been reduced to a desired value it is likely to remain at that temperature for a period which may range from a few hours, for chilled products, to a number of years in the case of frozen foods. During that period it may remain in a single store or be transported around the world. In practice there are many problems in meat storage and transport because the meat and meat products are not at the correct temperature when they are loaded. If the temperature of the meat is too high when it is wrapped and bulk packaged then it becomes very difficult to reduce that temperature within the storage or transport compartment. Since these systems are not designed to extract heat then the average room temperature can rise together with that of any other foods already stored. Failure to remove the required heat before loading can be due to a number of causes including: insufficient time allowed, insufficient refrigeration capacity to cater for high initial product load, overloading, variability in size of products or incorrect environmental conditions. Theoretically, there should be few problems in the storage and transport of either chilled or frozen foods. If the meat is at the correct temperature when it is loaded into the storage room or transport vehicle then all the refrigeration is required to do is to insulate the meat from sources of heat. If the standard of management is good, and the meat bulk stacked, then temperature rise in the meat

will be small and restricted to exposed surfaces.

Retail display

Retail display cabinets can have integral or remote refrigeration units, air movement can be gravity or forced air and the displays can be single-tier, multi-tier or well. Chilled meat products spend periods ranging from a few minutes to a week in retail display and in extreme cases with frozen products a few months.

Domestic transport and storage

After the meat is removed from a display cabinet it spends a period outside a refrigerated environment whilst it is carried around the store and then transported home. Temperatures of foods, especially thin sliced products, can rise considerably during these journeys. Consumers have considerable faith in the temperature maintenance properties of domestic refrigerators that operated at mean temperatures that would support the growth of salmonella (James 2002).

The Effect of Freezing and Thawing on Meat Quality

Studies have shown that freezing rate influences ice crystal size, location (intra - or extra - cellular), and morphology (Christian and Stephen 2010; Grujic *et al.* 1993).

There is a general view that fast freezing offers some quality advantage, with “ quick frozen ” appearing on many meat products with the expectation that consumers will pay more for a quick - frozen product. In general, the method of freezing or the rate of freezing has any substantial influence on the quality characteristics or final eating quality of meat. In a study comparing frozen beef burgers, no significant difference could be seen in cooking losses or eating quality between samples frozen using either spiral, impingement, or cryogenic methods, even after 2 months storage (Sundsten *et al.* 2001). In terms of increased throughput, however, the study did reveal some slight commercial advantages of fast freezing. The meat is cooled under high pressure to sub - zero temperatures but does not undergo a phase change and freeze until the pressure is released. Rapid

nucleation results in small even ice crystals. However, studies on pork and beef (Fernandez - Martin *et al.* 2000) and on pork (Zhu *et al.* 2004) failed to show any real commercial quality advantages, and an increase in toughness was found in the later study. High pressure freezing and in particular “ pressure shift ” freezing is attracting considerable scientific interest (LeBail *et al.*, 2002).

The effect of chilling and freezing on meat tenderness and texture

Tenderness is the major characteristic of eating quality because it determines the ease with which meat can be chewed and swallowed. The tenderness of meat is affected by both chilling/freezing and storage. Refrigeration has two critical roles in meat tenderness. One is in the prevention of muscle shortening in the period immediately following slaughter. The second is in the conditioning of the meat so that the desired degree of tenderness is obtained. Under the proper conditions, tenderness is well maintained throughout the chilled/frozen storage life, but improper chilling/freezing, can produce severe toughening and meat of poor eating quality (James 2002). To quote an Australia CSIRO report (1988) ‘Toughness (in meat) is caused by three major factors – advancing age of the animal, ‘cold shortening’ (the muscle fibre contraction that can occur during chilling) and unfavourable meat acidity (pH).’ There is general agreement on the importance of these factors, with many experts adding cooking as a fourth, equally important, influence. Chilling has serious effects on the texture of meat if it is carried out rapidly when the meat is still in the pre-rigor condition, that is, before the meat pH has fallen below about 6.2 (Bendall, 1972). In this state the muscles contain sufficient amounts of the contractile fuel, adenosine triphosphate (ATP), for forcible shortening to set in as the temperature falls below 11°C, the most severe effect occurring at about 3°C (James 2002). The major increase in tenderness has been shown to occur in less than 14 days in beef. Buchter (1970) showed that no significant increase in tenderness occurs after 4 to 5 days for calves and 8 to 10 days for young bulls at 4 °C.

Freezing rate affects the rate of tenderising after thawing but not the ultimate tenderness. Freezing at -10°C more than doubles the rate; freezing in liquid nitrogen almost trebles the rate. Freezing is known to cause structural damage by ice crystal formation. It seems likely that ice crystals, particularly small intracellular ice crystals formed by very fast freezing rates, enhance the rate of conditioning probably by release of enzymes (Dransfield, 1986). Repeated freeze-thaw cycles using relatively low freezing rates does not seem to cause any enhanced tenderising (Locker and Daines, 1973). In a study by Martin *et al.* (1971), in which more than 500 animals were examined, it was concluded that, for beef carcasses, an ageing period of 6 days was sufficient for a consumer product of satisfactory tenderness. The merits of 'dry' versus 'wet' ageing are an ongoing matter of debate. What is clear is that there is greater

shrink, weight loss and trim loss associated with dry ageing and hence the process is more expensive than wet ageing. In the UK, ageing has seen a revival in recent years and UK supermarkets are currently marketing beef aged for up to 28 days, lamb aged for 14 days and pork aged for 10 days. In common with the accepted practice of hanging game birds, the hanging of turkeys is also receiving increased interest. Although ageing is rapid in poultry meat, deboning before sufficient tenderization has taken place can result in tough meat. Studies to determine the minimum amount of ageing required before deboning show that at least 2 and possibly 4 hours are required in chicken (Sams, 1999) and at least 6 and possibly 8 hours in turkeys (Fanatico, 2003). Time taken to achieve 50 and 80% ageing at 1 °C for different species is shown in table 1.

Table 1. Time taken to achieve 50 and 80% ageing at 1 °C for different species (James 2009).

species	Time (d) taken to achieve	
	50%	80%
Beef	4.3	10.0
Veal	4.1	9.5
Rabbit	4.1	9.5
Lamb	3.3	7.7
Pork	1.8	4.2
chicken	0.1	0.3

There is little evidence of any relationship between chilling rates and subsequent frozen storage-life. However, there is evidence for a relationship between frozen storage-life and the length of chilled storage (ageing) prior to freezing. It has been shown that pork that has been held for 7 days prior to freezing deteriorates at a faster rate during subsequent frozen storage than carcasses chilled for 1 and 3 days prior to freezing (Harrison *et al.*, 1956). Chilled storage of lamb for one day at 0 °C prior to freezing can reduce the subsequent storage life by as much as 25% when compared to lamb which has undergone accelerated conditioning and only 2 hours storage at 0 °C (Winger, 1984).

The impact of chilling and freezing on meat colour

and Appearance

There is an interaction between the colour of meat after thawing and its freezing rate. Red colour is more stable at lower temperatures because the rate of oxidation of the pigment decreases. At low temperatures, the solubility of oxygen is greater and oxygen consuming reactions are slowed down. There is a greater penetration of oxygen into the meat and the meat is redder than at high temperatures (James 2002). Jakobsson and Bengtsson (1973) found that slowly frozen beef, which darkened on freezing also, showed considerable loss of redness after thawing. In contrast, meat frozen in liquid nitrogen and then defrosted was a light, bright red. Little difference was also found between thawed beef steaks which were frozen at 15 cm hr⁻¹ in liquid nitrogen spray and

those which were blast frozen at 4 cm hr⁻¹ (Pap, 1972).

Meat, which has lost its attractiveness during frozen storage because of oxidation of oxymyoglobin on the surface, will remain brown after thawing (James and James 2009). Meat, when cut and exposed to air, changed from dull purple red to a bright cherry red, which is measured as an increase in 'lightness', a 'hue' change towards red and an increase in 'saturation'. The magnitude of the change on blooming for conditioning meat as compared with unaged was the

same size for 'lightness' but was twofold greater for 'hue' and threefold greater for 'saturation'. Conditioned meat, when freshly cut, was lighter but more purple than the unconditioned. After one hour exposure to air, conditioned meat had a redder 'hue' which was considerably more saturated and intense than the unconditioned samples. These changes in lightness, hue and saturation produced by conditioning result in a brighter, more attractive appearance. The overall colour improvement was of a similar magnitude to that which occurred on Blooming (James 2002).

Table 2. Advantages and disadvantages of different thawing systems (Christian and Stephen 2010).

		ADVANTAGES	DISADVANTAGES
Conduction systems	AIR	Easy to install: can be adapted from chill rooms. Low velocity systems retain good appearance.	Very slow, unless high velocities and high temperatures are used, when there can be weight loss, spoilage and appearance problems.
	WATER	Faster than air systems.	Effluent disposal. Deterioration in appearance and microbiological condition. Unsuitable for composite blocks.
	VACUUM - HEAT (VHT)	Fast. Low surface temperatures. Very controllable. Easily cleaned.	Deterioration in appearance. High cost. Batch size limited.
	HIGH PRESSURE	Fast. Reduces microorganisms.	Not commercially available at present.
Electrical systems	MICROWAVE/INFRA RED	Very fast.	Problems of limited penetration and uneven energy absorption. Can cause localized 'cooking'.
	RESISTIVE	Fast.	Problems of contact on irregular surfaces.
	ULTRASONIC	Fast.	Not commercially available at present

Unwrapped meat thawed in high humidity air, water or in steam under vacuum appears very white and milky after thawing. However, if then stored in a chill room for 10 to 24 hours, it will be almost indistinguishable from fresh meat. Unwrapped meat thawed in air at high temperatures and low humidities will take on a dark, dry, tired appearance. It will not recover its appearance during chilled storage and will often require extensive trimming before sale (James and James, 2002). The colour of frozen meat varies with the rate of freezing. Experiments have demonstrated a direct relationship between freezing rate and muscle lightness; the faster the rate the lighter the product (James, 2002). In thawed meat, the rate of pigment oxidation is increased and therefore the colour will be less stable than in fresh. On prolonged frozen storage, a dark brown layer of metmyoglobin may form 1–2 mm

beneath the surface so that on thawing, the surface colour will rapidly deteriorate (James and James, 2009).

Changes in appearance are normally the criteria that limit the display life of unwrapped products, rather than microbiological considerations. Deterioration in the appearance of unwrapped meats has been related to the degree of dehydration, which makes the product unattractive to consumers (James and Swain, 1986). The rate of dehydration is a function of the temperature, velocity and especially the relative humidity of the air passing over the surface of the meat on display. Reducing the relative humidity from 95 to 40% can increase the rate of dehydration by a factor of 18. The appearance of meat at its point of sale is the most important quality attribute governing its purchase. Changes in colour of the muscle and

blood pigments (myoglobin and haemoglobin, respectively) determine the attractiveness of fresh red meat, which in turn influences the consumers' acceptance of meat products (Pearson, 1994).

'Freezer burn' is the main appearance problem that traditionally affected the appearance of meat in frozen storage. Desiccation from the surface tissues produces a dry, spongy layer that is unattractive and does not recover after thawing. This is commonly called 'freezer-burn'. It occurs in unwrapped or poorly wrapped meat. The problem is accentuated in areas exposed to low humidity air at high velocities, and by poor temperature control. Since most meat is now wrapped and temperature control much improved, this is less of a problem than it once was, commercially. Provided problems of freezer burn can be eliminated, the major appearance problem that affects frozen meat arises from oxidation of oxymyoglobin to metmyoglobin. Both temperature and illumination level affect the rate of discoloration during frozen storage, but light is by far the more serious factor (James and James, 2009).

Odor and Flavor

meat flavor can alter during frozen storage. This is principally caused by lipid (fat) oxidation, also referred to as oxidative rancidity, which results in unacceptable "off" or "rancid" flavors. The importance of lipid oxidation in frozen meat may be illustrated by a short quotation from a paper published by Lea (1931): "it is often the deterioration of the fat which limits the storage life — from the point of view at least of palatability — of the meat." This view has been reiterated many times since (Morrissey *et al.* 1998), and as freezing technology has improved, it is true to say that lipid oxidation remains the obstacle to very long term storage of frozen meat.

The reaction of oxygen with fat is an autocatalytic process (Enser 1984). Once the reaction starts, the products of the reaction stimulate it to go faster. The initial reaction is that between a molecule of oxygen and a fatty acid to form a peroxide. This is a slow

reaction but, like any other chemical reaction, raising the temperature increases its rate (Christian and Stephen 2010). The presence of peroxides in fat does not change the flavor; it is the breakdown products of the peroxides that produce the rancid odor and flavor. The breakdown of peroxide is accelerated by heat, light, organic iron catalysts, and traces of metal ions, especially copper and iron. It is also the breakdown products of the peroxides that cause the oxygen to react more rapidly with the fatty acids, thus producing the autocatalytic effect.

The type of fatty acid influences the rate. Saturated fatty acids react slowly, but unsaturated fatty acids react more rapidly, and the more double bonds that a fatty acid contains, the more reactive it is. There is considerable evidence that dietary vitamin E supplementation reduces lipid oxidation (Morrissey *et al.* 1998). It is less clear what other components of the diet may beneficially effect lipid stability (Morrissey *et al.* 1998). This process can also be significantly slowed in frozen meat if oxygen is completely eliminated and the storage temperature is extremely low (i.e., under -60°C) (Pérez Chabela and Mateo - Oyague 2006). The development of oxidative rancidity in meat is affected by many factors (Pérez Chabela and Mateo - Oyague 2006), some intrinsic (such as species, muscle type, amount and type of fat in the diet, enzymes), others extrinsic (such as light, heat, damage to muscle structures caused by freezing, mincing, and the addition of sodium chloride).

The impact of chilling and freezing on drip production

Drip loss occurs throughout the cold chain and represents a considerable economic loss to the red meat industry. The potential for drip loss is inherent in fresh meat and is related to the development of rigor mortis in the muscle after slaughter and its effect on pH. It is influenced by many factors. Some of these, including breed, diet and physiological history, are inherent in the live animal. Others, such as the rate of chilling, storage temperatures, freezing and thawing, occur during processing. Drip can be

referred to by a number of different terms including 'purge loss', 'press loss' and 'thaw loss', depending on the method of measurement and when it is measured. The protein concentration of drip is about 140 mg ml^{-1} , about 70% of that of meat itself. The proteins in drip are the intracellular, soluble proteins of the muscle cells. The red colour is due to the protein myoglobin, the main pigment of meat (James and James, 2009).

Drip potential clearly appears to be related to species. In general, poultry meat is far less prone to drip. In pigs, especially, there are large differences in drip loss from meat from different breeds. Beef tends to lose proportionately more drip than pork and lamb.

There can be large differences in drip loss between different muscles. Rapid chilling reduces drip loss after subsequent cutting operations. The potential for drip loss is established in the first period of cooling; the temperature range conducive to drip is down to about 30°C , or perhaps a little lower. The resulting plot of drip loss against cooling rate is shown in Fig 1.

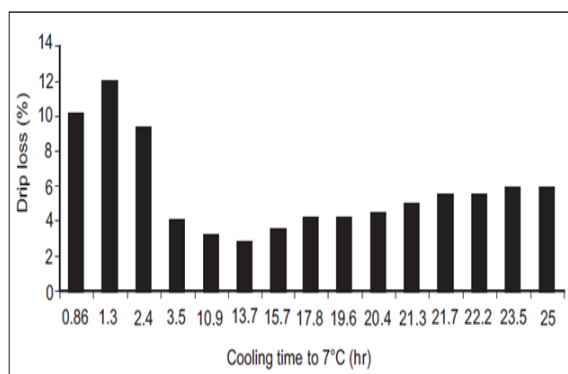


Fig. 1. Percentage drip loss from beef sample as a function of cooling time (hours) to 7°C (source: Gigiel *et al.*, 1985).

Freezing Systems for Meat

Heat transfer can only occur by four basic mechanisms: conduction, radiation, convection, and evaporation/condensation. Convection is by far the most important heat transfer mechanism employed in the majority of meat refrigeration systems. In most cases, refrigerated air is the transfer medium; however, in some cases water, brine, or a cryogenic gas can be used. Evaporation from a meat surface

reduces yield and is not desirable in most meat refrigeration operations but can be useful again in the initial cooling of cooked meat products. In primary freezing, radiation is only important in the initial stages of the process in a system where the meat is not surrounded by other product. Again, in the initial stages of the freezing of cooked meat products (e.g., pies, pasties, joints), radiant heat loss can be substantial if the products are surrounded by cold surfaces. Conduction requires a good physical contact between the meat to be cooled and the cooling medium, and this is generally difficult to achieve with carcasses and other irregular meat cuts. Radiation does not require any physical contact, but a large temperature difference is required between the surface of the meat being cooled and that of surrounding surfaces to achieve significant heat flow (Christian and Stephen 2010).

Thawing and Tempering Systems for Meat

Thawing is usually regarded as complete when the center of the block has reached 0°C , the minimum temperature at which the meat can be filleted or cut by hand. Lower temperatures (e.g., -5 to -2°C) are acceptable for meat that is destined for mechanical chopping, but such meat is "tempered" rather than thawed.

The two processes should not be confused because tempering only constitutes the initial phase of a complete thawing process. In practice, tempering can be a process in which the temperature of the product is either raised or lowered to a value that is optimal for the next processing stage. Thawing is often considered as simply the reversal of the freezing process. However, inherent in thawing is a major problem that does not occur in the freezing operation. Tempering systems where the temperature of frozen product is lowered will be covered in the tempering and crust – freezing section.

The majority of the bacteria that cause spoilage or food poisoning are found on the surfaces of meat. During the freezing operation, surface temperatures are reduced rapidly, and bacterial multiplication is

severely limited, with bacteria becoming completely dormant below -10°C . In the thawing operation, these same surface areas are the first to rise in temperature, and bacterial multiplication can recommence.

On large objects subjected to long uncontrolled thawing cycles, surface spoilage can occur before the center regions have fully thawed.

Most systems supply heat to the surface and then rely on conduction to transfer that heat into the center of the meat. A few use electromagnetic radiation to generate heat within the meat.

In selecting a thawing system for industrial use, a balance must be struck between thawing time, appearance, the bacteriological condition of the product, processing problems such as effluent disposal, and the capital and operating costs of the respective systems. Of these factors, thawing time is the principal criterion that governs selection of the system. Appearance, bacteriological condition, and weight loss are important if the material is to be sold in the thawed condition but are less so if the meat is for processing. Thawing time depends on factors relating to the product and the environmental conditions and include:

1. dimensions and shape of the product, particularly the thickness,
2. change in enthalpy,
3. thermal conductivity of the product,
4. initial and final temperatures,
5. surface heat transfer coefficient, and
6. temperature of the thawing medium.

There are two basic methods of thawing:

thermal and electrical. Thermal methods are dependant upon conventional heat conduction through the surface. Electrical methods, on the other hand, employ heat generation inside the product. There is no simple guide to the choice of an optimum thawing system (Table 2).

A thawing system should be considered as one operation in the production chain. It receives frozen

material, hopefully, within a known temperature range and of specified microbiological condition. It is expected to deliver that same material in a given time in a totally thawed state. The weight loss and increase in bacterial numbers during thawing should be within acceptable limits, which will vary from process to process.

Conclusion

Temperature control is a key element in improving the safety and eating quality of the meat, this has led to more emphasis being placed on the design and operation of meat refrigeration processes. One key development has been the reintroduction of ageing (maturing) rooms for beef, lamb and more recently pork and turkey. It is expected that aged meat will take up a higher percentage of the total market in the future. In the past decade, the use of impingement technology to increase the surface heat transfer in freezing systems has received attention. Under commercial conditions, differences in freezing rates are unlikely to produce noticeable changes in the organoleptic quality of the meat produced. However, current legislation requires a minimum meat temperature of -12°C to be achieved before meat is moved from the freezing system. Freezing time is therefore of considerable economic importance (Christian and Stephen 2010).

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