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Review Article

The primary chilling of poultry carcasses—a review

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Abstract

This paper reviews the published scientific studies that have been carried out on the chilling of poultry carcasses. The prime purpose of chilling is to limit the growth of both pathogenic and food spoilage microorganisms. There are a wide range of publications that show that, in general, the numbers of both types of microorganism, on the surface of poultry carcasses, is reduced during the chilling process. Immersion or spin chilling is not used in the production of 'fresh' chilled poultry in Europe, 'dry' air chilling being the preferred chilling method. Many people believe that there is some clear microbiologically based reason behind the selection of air chilling. However, the published data do not appear to support this belief, and if anything point to a microbial advantage of immersion systems. The rate of chilling has some influence on the taste, texture and appearance of poultry meat. Very rapid chilling can result in tougher chicken meat, while very slow chilling can produce pale soft exudative (PSE) muscle. However, in both cases the effect is not as marked as with red meat. No comprehensive published data has been found on the effect of a range of chilling systems, chilling conditions, carcass weight and shape on the rate of chilling, weight loss and heat loss. Without such data it is impossible to optimise the design of a poultry chilling system.

Keywords: Poultry; Survey; Process; Chilling

Réfrigération des carcasses de poulet: tendances

Mots clés : Volaille ; Enquête ; Procédé ; Réfrigération

1. Introduction

After slaughter a poultry carcass has to be chilled to reduce and then maintain the temperature of the meat below a value that will ensure a high quality, safe product. There is no legislation in the European Union governing the time required to chill a poultry carcass, only a maximum final meat temperature of 4 °C before transport or cutting is defined, to be achieved 'as soon as possible' [1]. Regulations in the United States require carcasses to be chilled to 4.4 °C or lower in 4, 6, or 8 h for carcasses weighing less than 4, 4–8, or over 8 pounds (⟨1.8, 1.8–3.6, or ⟩ 3.6 kg), respectively [2]. The internal deep breast has been identified as the slowest cooling position in a chicken carcass [3]. An unpublished survey of chilling conditions in four UK commercial poultry processing plants conducted recently by

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the authors of this paper showed that deep breast temperatures measured in 257 carcasses immediately before entering the chillers ranged from 29.6 to 42.4 °C (mean (SD) temperature of 37.7 (2.4) °C).

2. Influence of chilling on product safety and quality

Primary chilling of poultry carcasses is carried out to produce a safe product by reducing the temperature of the meat to a point where the rate of growth of spoilage microorganisms is reduced and the growth of most pathogenic microorganisms is prevented. It also has an effect on the major quality indicators of flavour, appearance and meat texture.

2.1. Microbiology

A number of bacterial pathogens capable of causing food poisoning in humans are known to contaminate poultry meat. The most important are *Salmonella* spp., *Campylobacter* spp., *Clostridium perfringens*, *Listeria monocytogenes* and Enterohaemorrhagic *Escherichia coli* [4]. In addition, Mead [5] states that two cold-tolerant types of bacteria, *Aeromonas* spp. and *Yersinia enterocolitica* are also found on poultry carcasses but have not been associated with foodborne illness. Minimum and optimum growth temperatures for pathogens commonly associated with poultry meat are shown in Table 1. Some pathogens, such as *L. monocytogenes*, are capable of growth at temperatures below 5 °C. These are often cited as being of particular concern in relation to refrigerated meats since refrigeration can not be relied on to prevent growth [6].

The number of types of microorganisms capable of causing food spoilage is very large. However, depending on the initial microflora and the growth environment, only a few species of the genera *Pseudomonas*, *Acinetobacter*, *Moraxella*, *Brochothrix thermosphacta*, *Aeromonas* spp. and *Psychrobacter* spp. and of the family *Enterobacteriaceae* are significantly represented in most spoilage microflora of chilled poultry meat [4].

A number of studies have looked at the effect of different chilling systems on the survival of both pathogenic and food spoilage organisms on poultry meat. Unfortunately, many studies do not quote the actual chilling conditions and the chilling rates used. Often where a comparison is made between different chilling methods (i.e. water immersion vs. air chilling) the rates of cooling may be very different and a 'like for like' comparison may not have been made. In addition, it is often difficult to distinguish between the effects of the chilling process alone and the effect of storage at a chilled temperature.

Air-borne cross-contamination is a worry in food processing operations. Ellerbroek [7] found a lower total viable count in the air of an air chiller than in an evaporative spray chiller, 3.28 $\log_{10}$ colony-forming units (cfu) m^{-3} and 4.16 $\log_{10}$ cfu m^{-3}, respectively. However, the numbers of *Enterobacteriaceae* were lower 3.30 $\log_{10}$ cfu m^{-3} and 1.34 $\log_{10}$ cfu m^{-3}, respectively.

2.1.1. Pathogenic bacteria

Campylobacter is the major cause of food poisoning in the UK and often associated with raw poultry meat. With *Campylobacter*, reductions of up to 2 $\log_{10}$ cfu ml^{-1} have been reported after water and immersion chilling (Table 2), though little change was reported in air chilling systems. These data were obtained using a whole carcass rinse technique. The bird is placed in a bag, a known amount of diluent added and the bag shaken. The diluant is then drained out and plated to obtain the bacteria numbers per ml of diluent.

Most studies on the effect of chilling on *Salmonella* have determined the prevalence on carcasses before and after chilling, rather than the numbers present (Table 2). Overall, the prevalence tended to be reduced by chilling but Morris and Wells [8] noticed an increase when carcasses were chilled by rotation in a ice slush, which they believed was due to cross-contamination caused by extensive contact between carcasses. The presence or absence of chlorine may also have had an influence, as James et al. [9,10] recorded increases in an immersion chiller without chlorine addition and no change with chlorine.

Water/immersion chilling also reduces the number of indicator organisms such as coliforms and *E. coli* (Table 3). Reductions of 1.1 $\log_{10}$ cfu ml^{-1} have been reported without chlorine and up to 2.5 $\log_{10}$ cfu ml^{-1} with the addition of chlorine. No significant reductions have been reported in studies investigating air chilling.

The potential decrease (or increase) in overall numbers during chilling is not the only effect observed on microorganisms. Newell et al. [20] showed that changes in the distribution of *Campylobacter* strains occurred during

Table 1
Minimum and optimum growth temperatures for pathogens associated with poultry meat [5]

	Minimum temperature (°C)	Optimum temperature (°C)
Campylobacter spp.	30	42–43
Clostridia perfringens	12	43–47
Pathogenic *Escherichia coli* strains	7	35–40
Salmonella spp.	5	35–43
Listeria monocytogenes	0	30–37
Yersinia enterocolitica	−2	28–29

Table 2
Data on the effects of chilling on *Salmonella* spp. and *Campylobacter* spp. during poultry carcass cooling

Chilling method	Details	Sampling methods	Unit	Before chilling	After chilling	Sources
Salmonella spp.						
Immersion	Rotation in an ice slush	Swab samples from chicken carcass	% of prevalence	4	11	[8]
	At least 4 °C after 1 h in the chiller	Whole carcass rinse technique	% of prevalence	48	72	[9]
	At least 4 °C after 1 h in the chiller, chlorinated water (25 ppm)	Whole carcass rinse technique	% of prevalence	43	46	[10]
	–	Whole carcass rinse	% positive	20	19	[11]
	20 ppm chlorinated water	Whole carcass rinse	$\log_{10}$ cfu per ml of rinse	1.3	0.8	[12]
	20 ppm chlorinated water	Whole carcass rinse	% positive carcasses	56	15	[12]
Air	Near 3 °C	Swab samples	% of prevalence	70	60	[13]
Spin	–	Swab samples from skin surface and body cavity of the whole bird	% positive	52	13	[14]
Campylobacter spp.						
Immersion	–	Whole carcass rinse	% positive	100	99	[11]
	–	Whole carcass rinse	$\log_{10}$ cfu per carcass	5.31	3.80	[11]
	–	Whole carcass rinse	$\log_{10}$ cfu per carcass	5.39	3.91	[11]
	20 ppm chlorinated water	Whole carcass rinse	$\log_{10}$ cfu per ml of rinse	2.9	1.6	[12]
	20 ppm chlorinated water	Whole carcass rinse	% positive carcasses	99	83	[12]
	30 min 1 °C	Whole carcass rinse	$\log_{10}$ cfu per ml of rinse	2.1	0.7	[15]
	30 min 1 °C 2% solution of Protecta II	Whole carcass rinse	$\log_{10}$ cfu per ml of rinse	2.1	0.01	[15]
Air	75 min at 0–5 °C	Neck-skin 'maceration'	Mean $\log_{10}$ cfu per g of carcass neckskin	5.5	5.3	[16]
	75 min at 0–5 °C	Neck-skin 'maceration'	Mean $\log_{10}$ cfu per g of carcass neckskin	4.7	4.6	[16]

processing and were most evident after chilling, indeed some *Campylobacter* subtypes surviving through carcass chilling. Jimenez et al. [18] observed that the proportion of *Enterobacteriaceae cloacae* over *E. coli* increased at the chilling step compared with the evisceration and inside–outside shower steps.

2.1.2. Spoilage bacteria

Many studies have been carried out on the effect of chilling on numbers of spoilage microorganisms. In general, studies show either no change or a reduction in bacterial levels (Table 4). Some differences are apparent between the three main chilling methods. Overall, immersion chilling using water or ice water mixtures tends to produce a larger reduction in the number of microorganisms than air or spray chilling methods. The addition of chlorine to immersion water tends to increase the reduction.

Only a limited number of publications directly compare the effect of different chilling methods on bacterial changes. Graw et al. [24,25] carried out an extensive study on the affect of different air and spray/evaporative chilling methods on the numbers of different spoilage bacteria (Table 5). They reported that during air chilling no change of the bacterial load on the skin and the visceral cavity was observed. Spray/evaporation chilling resulted in a decrease of the skin's contamination by about half a log unit but had no impact on the visceral cavity load. Six commercial chilling systems were studied by Allen et al. [17], one water chiller, four air chillers with water sprays and one 'dry' air chiller. Bacterial counts were reduced during water chilling, but no overall effect was found on microbial contamination of the skin of carcasses chilled in the various air chillers. However, body cavity counts were reduced, by approximately one log unit/body cavity, more in the 'dry' air chiller than in the air chillers with water sprays. In one of the air chillers where non-chlorinated spray water was used an increase in pseudomonads was observed. Burton and Allen [26] noticed no significant overall change (below 0.5 $\log_{10}$ units) in the level of coliforms, pseudomonads or aerobic plate count on the skin during

Table 3
Data on the effects of chilling on coliforms and *Escherichia coli* during poultry carcass cooling

Chilling method	Details	Sampling method	Unit ($\log_{10}$ cfu)	Before chilling	After chilling	Sources
Coliforms						
Immersion	30 min 1 °C	Whole carcass rinse	per ml of rinse	2.5	1.4	[15]
	30 min 1 °C 2% solution of Protecta II	Whole carcass rinse	per ml of rinse	2.5	0.04	[15]
	25 ppm chlorinated water	Whole carcass rinse	per ml of rinse	3.36	2.65	[18]
	40 min at 5 °C 45 ppm chlorinated water	Body cavity rinse	per ml of rinse		1.28 reduction	[17]
	40 min at 5 °C 45 ppm chlorinated water	Neck skin	per g carcass neckskin		1.10 reduction	[17]
	25 ppm chlorinated water	Whole carcass rinse	per ml of rinse	3.36	2.65	[18]
	25 ppm chlorinated water	Whole carcass rinse	per ml of rinse	3.91	2.68	[18]
Air	75 min at 0–5 °C	Neck-skin 'maceration'	per g carcass neckskin	5.1	4.3	[16]
	75 min at 0–5 °C	Neck-skin 'maceration'	per g carcass neckskin	5.2	5.0	[16]
	–	Whole carcass rinse	per ml of rinse	3.27	2.59	[19]
Escherichia coli						
Immersion	At least 4 °C after 1 h	Whole carcass rinse	per carcass	1.46	0.87	[9]
	At least 4 °C after 1 h chlorinated water (25 ppm)	Whole carcass rinse	per carcass	2.04	1.20	[10]
	20 ppm chlorinated water	Whole carcass rinse	per ml of rinse	3.2	1.8	[12]
	25 ppm chlorinated water	Whole carcass rinse	per ml of rinse	3.44	2.28	[18]
	25 ppm chlorinated water	Whole carcass rinse	per ml of rinse	2.49	1.60	[18]
	30 min 1 °C	Whole carcass rinse	per ml of rinse	2.0	0.9	[15]
	30 min 1 °C 2% solution of Protecta II	Whole carcass rinse	per ml of rinse	2.0	0	[15]
Air	75 min at 0–5 °C	Neck-skin 'maceration'	per g carcass neckskin	4.8	4.4	[16]
	75 min at 0–5 °C	Neck-skin 'maceration'	per g carcass neckskin	4.2	4.1	[16]
	–	Whole carcass rinse	per ml of rinse	3.08	2.2	[19]

the complete chilling operation with chillers using water sprays (with and without chlorination) and dry chillers.

2.1.3. Overall

Immersion chilling is not now commonly used in the production of 'fresh', chilled poultry in Europe, 'dry' air chilling being the preferred chilling method. There is a common belief in Europe that there is some clear microbiologically based reason behind the selection of air chilling. The published data do not appear to support this belief and, if anything, point to a possible hygienic advantage of immersion systems, as Brant [27] was at pains to point out when the EU considered banning water immersion in the 1970s. Cross-contamination has been considered to be one of the major problems with immersion chilling, however, a study by Mead et al. [28] provides evidence that microbial cross-contamination can also occur during air chilling of poultry, whether or not water sprays are incorporated in the chilling process. Problems of cross-contamination in air chillers were also highlighted by Jul [29]. The notion that surface drying during air chilling should reduce the water activity and hence prolong shelf life has been postulated [30]. However, there does not appear to be any clear published evidence to support such a view. Thomas [30] suggested that this was perhaps due to the higher bacterial counts on air chilled carcasses off-setting any initial inhibition of growth as a result of a reduced water activity. It was also thought likely that the surface water activity soon returns to normal, i.e. close to 1, when the carcasses are packaged, or when storage conditions are poor. The current desire of the poultry industry to reduce weight losses during chilling certainly necessitates far less surface drying than may have previously occurred. Another reason suggested for the higher microbial counts reported on air chilled carcasses has been the lower scalding temperatures used [30] for air chilled carcasses.

2.2. Flavour

Refrigeration processes can influence the cooked flavour of poultry and poultry products; however, the main effects take place during storage rather than chilling.

Table 4
Data on the effects of chilling on aerobic plate counts during poultry carcass cooling

Chilling method	Details	Sampling methods	Unit (log_{10} cfu)	Before chilling	After chilling	Sources
Immersion	Slush-ice 25 min	Swab breast skin	per cm^2	3.17	2.57	[21]
Combined	25 min slush ice +45 min at −7 °C air blast	Swab breast skin	per cm^2	3.17	2.64	[21]
Combined	Tap water followed by slush ice	Swab breast skin	per cm^2	3.1	2.5	[22]
Immersion	Water, 30 min 1 °C	Whole carcass rinse	per ml of rinse	3.7	1.4	[15]
	Water, 30 min 1 °C 2% solution of Protecta II	Whole carcass rinse	per ml of rinse	3.7	0.06	[15]
	Water, 3 °C 45 min	Swab test	per cm^2	3.35	2.99	[23]
	Water, 3 °C 45 min 50 ppm chlorine	Swab test	per cm^2	3.35	2.72	[23]
	Water, 3 °C 45 min 50 ppm Glutaraldehyde	Swab test	per cm^2	3.35	2.74	[23]
	Water, at least 4 °C after 1 h	Whole carcass rinse technique	per carcass	3.39	3.14	[9]
	At least 4 °C after 1 h chlorinated water (25 ppm)	Whole carcass rinse technique	per carcass	3.20	2.51	[10]
	Immersion	Whole carcass rinse	per carcass	7.12	5.39	[11]
	Immersion	Whole carcass rinse	per carcass	7.13	5.27	[11]
Air	75 min at 0–5 °C	Neck-skin 'maceration'	per g carcass neckskin	4.8	4.4	[16]
	75 min at 0–5 °C	Neck-skin 'maceration'	per g carcass neckskin	4.2	4.1	[16]
	−7 °C, 3.5 ms^{-1}	Swab breast skin	per cm^2	3.1	2.7	[22]
	−40 °C	Swab breast skin	per cm^2	3.1	3.1	[22]
	2–3 ms^{-1} 2 °C 55 min		per g skin	4.77	4.78	[24]
	5–8 ms^{-1} 3 °C 75 min		per g skin	5.62	5.51	[24]
	2–3 ms^{-1} 2 °C 55 min	Visceral cavity rinse	per ml	3.75	3.73	[24]
	5–8 ms^{-1} 3 °C 75 min	Visceral cavity rinse	per ml	3.70	3.72	[24]
	–	Whole carcass rinse	per ml of rinse	3.81	3.23	[19]
Spray	2–3 ms^{-1} 2 °C 55 min		per g skin	4.73	4.29	[24]
	5–8 ms^{-1} 3 °C 60 min 1.4 l		per g skin	5.73	5.22	[24]
	2–3 ms^{-1} 2 °C 55 min	Visceral cavity rinse	per ml	3.70	3.69	[24]
	5–8 ms^{-1} 3 °C 60 min 1.4 l	Visceral cavity rinse	per ml	3.49	3.45	[24]

CFU, colony forming units.

Those studies that have reported the effects of chilling on flavour show conflicting results. There has been an assumption that flavour substances may leach out during immersion chilling [31], however, there are little published data to support this view [29]. Hale and Stadelman [32] and Hale et al. [33] reported that commercially processed, 'dry' (air) chilled broilers had a subtle, but detectable flavour advantage over 'conventional' (immersion) chilled broilers. On the other hand, Zenoble et al. [34] and Pedersen [35] found no effect of chilling on meat flavour and Ristic [36] found that water chilling of broilers produced a more favourable flavour than air chilling for both leg and breast meat. In his review of chilling systems, Lillard [37] stated that improved flavour is one of the particular claims for chilling systems using liquid nitrogen or carbon dioxide. However, again there would appear to be little published data to support this supposition. Brodine and Carlin [38] investigated three chilling methods for turkeys prior to freezing that utilised a spin chiller: 1 h spin, 1 h spin plus three hours in slush ice, 1 h spin plus 23 h in slush ice. None of the chilling methods had any effect on either flavour or juiciness of cooked breast or thigh meat.

2.3. Appearance

The appearance of poultry meat has a substantial effect on its sales appeal, and different chilling methods can influence this aspect of product quality. The scalding the carcasses have received prior to chilling has a marked effect on the final appearance [29]. Carcasses destined for air chilling can only be 'soft' scalded (i.e. at 50–53 °C). This retains the outer dermal layer. Higher scalding temperature removes the outer dermal layer and makes the carcasses more susceptible to dehydration and discolouration if air chilling is used. The problem does not occur with immersion chilled carcasses that can be 'hard' scalded at higher temperatures. This difference in processing makes comparing the effect of different chilling methods difficult.

Table 5
Data on the effects of chilling on some spoilage organisms [25]

Chilling method	Details	Bacterial type	Before chilling	After chilling
Air	2–3 ms^{-1} 2 °C 55 min	*Micrococcaceae*	4.56	4.50
	5–8 ms^{-1} 3 °C 75 min	*Micrococcaceae*	5.34	5.23
	2–3 ms^{-1} 2 °C 55 min	GPIS	3.81	3.83
	5–8 ms^{-1} 3 °C 75 min	GPIS	5.03	4.97
	2–3 ms^{-1} 2 °C 55 min	*Streptococcus* spp.	3.26	3.21
	5–8 ms^{-1} 3 °C 75 min	*Streptococcus* spp.	4.39	4.20
	2–3 ms^{-1} 2 °C 55 min	*Lactobacillus* spp.	3.24	3.60
	5–8 ms^{-1} 3 °C 75 min	*Lactobacillus* spp.	2.18	2.01
	2–3 ms^{-1} 2 °C 55 min	*Aerococcus* spp.	1.77	2.29
	2–3 ms^{-1} 2 °C 55 min	*Alcaligenes* spp.	2.06	2.06
	5–8 ms^{-1} 3 °C 75 min	*Alcaligenes* spp.	3.90	3.55
	2–3 ms^{-1} 2 °C 55 min	*Flaviobacterium* spp.	2.53	2.61
	5–8 ms^{-1} 3 °C 75 min	*Flaviobacterium* spp.	4.02	3.67
	5–8 ms^{-1} 3 °C 75 min	*Acinetobacter* spp.	2.28	3.02
Spray	2–3 ms^{-1} 2 °C 55 min	*Micrococcaceae*	4.34	3.87
	5–8 ms^{-1} 3 °C 60 min, 1.4 l	*Micrococcaceae*	5.48	4.95
	2–3 ms^{-1} 2 °C 55 min	GPIS	4.10	3.77
	5–8 ms^{-1} 3 °C 60 min, 1.4 l	GPIS	5.00	4.59
	2–3 ms^{-1} 2 °C 55 min	*Streptococcus* spp.	3.58	3.12
	5–8 ms^{-1} 3 °C 60 min, 1.4 l	*Streptococcus* spp.	4.53	3.97
	2–3 ms^{-1} 2 °C 55 min	*Lactobacillus* spp.	3.52	2.88
	5–8 ms^{-1} 3 °C 60 min, 1.4 l	*Lactobacillus* spp.	1.54	2.14
	2–3 ms^{-1} 2 °C 55 min	*Aerococcus* spp.	0	0
	2–3 ms^{-1} 2 °C 55 min	*Flaviobacterium* spp.	3.14	2.70
	5–8 ms^{-1} 3 °C 60 min, 1.4 l	*Flaviobacterium* spp.	4.35	3.88
	2–3 ms^{-1} 2 °C 55 min	*Alcaligenes* spp.	2.98	2.73
	5–8 ms^{-1} 3 °C 60 min, 1.4 l	*Alcaligenes* spp.	4.12	3.01
	5–8 ms^{-1} 3 °C 60 min, 1.4 l	Acinetobacter	1.97	2.54

GPIS, Gram-positive irregular rods.

With 16 kg turkey carcasses, Evans et al. [39] found that chilling at an air speed of 3.0 ms^{-1} and a temperature of 0 °C with spraying for 60 s at 20 min intervals during the first half of the chilling period produced the 'best' appearance. Chilling in air at 3.0 or 0.2 ms^{-1} and 0 °C without sprays produced birds of slightly inferior appearance. Mielnik et al. [40] studied the effect of spray-air chilling on the quality of fresh chicken carcasses, when compared with air chilling as a reference method. The chilling method affected the skin colour and the amount of moisture on the surface of the skin. After spray-air chilling, the carcasses had a lighter colour and there was more water on the back and under the wings. Lyon and Lyon [41] state that discolouration of raw or cooked tissue can occur from cell disruption and blood migration caused by slow or variable chilling rates.

2.4. Texture

The textural problems found in red meat caused by slow chilling ('pale, soft, exudative' (PSE) meat) or rapid chilling ('cold shortening') are also present in poultry meat, though to a lesser extent.

Pale, soft, exudative (PSE) meat has been reported to be a growing problem in the poultry industry (particularly regarding turkeys) and is characterized by a rapid post-mortem pH decline [42]. The low pH condition while the body temperature remains high leads to protein denaturation, causing a pale colour and reduced water-holding properties [43]. Lesiak et al. [44] reported that holding excised turkey breasts for 15, 60 or 120 min in a water bath at 30 °C before chilling resulted in drip losses of 0.5, 1.17 and 1.6%, respectively. Rapid chilling should alleviate this problem and it has been recommended that deep muscle temperatures in turkeys should be reduced below 25 °C by 60 min post-mortem [45].

Conversely rapid chilling, prior to rigor mortis development, can toughen meat through the process known as 'cold shortening' [46]. Although poultry breast muscles are primary composed of white fibres [47], which are less prone to cold shortening than the red fibres found in red meats, cold shortening has been shown to occur [48,49].

Poultry meat does not require the same amount of ageing as red meat to develop its optimum texture. The 1st order rate constant at 1–4 °C (derived from the exponential decay of toughness of cooked muscles with time) is 5.2 $days^{-1}$.

Thus 50% of the tenderising occurs in about 3 h and 80% in 10 h [50], with high tenderness scores being recorded for carcasses aged for 24 h [51]. Studies to determine the minimum amount of aging required before deboning show that at least 2 and possibly 4 h are required in chicken [47] and at least 6 and possibly 8 h in turkeys [52]. Though, as Sams [47] stresses, 'there are many degrees of tenderness and the definition of tender meat varies among cultures and geographic regions'.

Post-mortem electrical stimulation (ES) is not a new technology but has only recently become used commercially in poultry processing. In poultry processing, ES seeks to reduce the toughness of meat that is deboned prior to the normal aging (or maturation) period [53]. On the poultry carcass, muscles are attached to the bone structure that limits the ability of the muscles to contract and toughen under rapid chilling regimes. Poultry also enters rigor much more quickly than meat so rapid chilling has less effect on tenderness.

Although many different ES techniques have been studied, the systems can be grouped into low amperage (0–200 mA per bird) and high amperage systems (350–500 mA per bird). The low amperage systems accelerate rigor development and prevent sarcomere shortening in the breast fillet after deboning, while the high amperage systems also induce the additional effect of myofibrillar damage to further improve tenderness [53]. Comprehensive reviews of ES in poultry have been carried out by Sams [53] and Li et al. [54], the theory by which ES may tenderise meat has been reviewed by Cross [55]. Although ES is now established in the red meat industry adoption of ES by the poultry industry remains slow. Craig et al. [56] attributed this to ES not being shown to consistently eliminate toughness or not sufficiently decreasing aging times to eliminate the need for large holding capacities.

Little has been published on the effect of chilling method on texture. A study by Arafa [57] indicated that chilling broilers in a liquid nitrogen spray tunnel results in lower shear values and longer sarcomere length that indicated more tender meat than broilers that were immersion chilled. Unfortunately there are no data on the rates of chilling in the paper, only that the broiler carcasses were removed before an immersion chilling stage and put through a commercial nitrogen tunnel for 8 min.

3. Primary chilling parameters

Brant [27], Thomson et al. [58], Thomas [30], Lillard [37] and Jul [29] have produced good overviews of the poultry primary chilling process. For red meat there are comprehensive data on the relationship between processing and carcass variables on chilling times, weight losses and refrigeration loads for beef sides [59], pork carcasses [60] and to a lesser extent lamb and goat carcasses [61]. However, there would appear to be a dearth of equivalent scientifically published information for poultry carcasses.

3.1. Operating costs

Calculating the operating costs of the various chilling methods is not an easy task. Lillard [37] considered immersion chilling in USA to be by far the most cost effective method, suggesting that spray chilling was economically and ecologically unacceptable, and air chilling less efficient and more expensive. Pederson [62] calculated the relative costs of five different chilling methods in Denmark. When only energy costs were considered, the cost of a counter-current water chilling system was one fifth that of an air chilling method. However, when the costs of the water and wastewater disposal were added, the water chilling cost was over 50 times that of the air system (Fig. 1). An immersion chiller operating with the water flowing in the opposite direction (counter flow) being slightly cheaper that one in

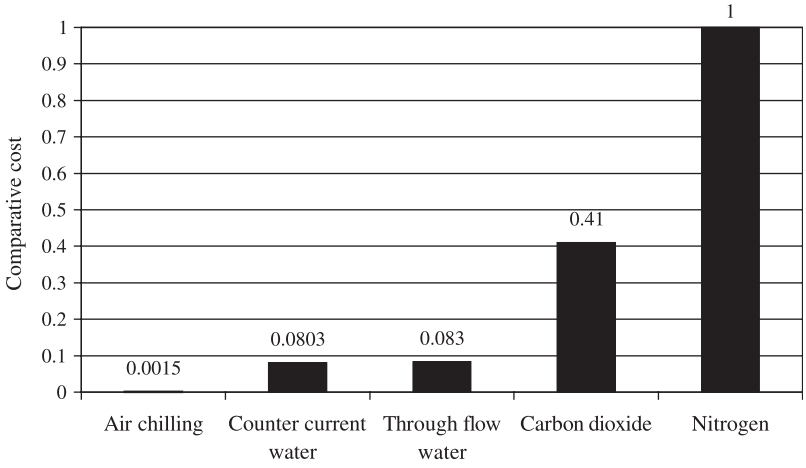

Fig. 1. Comparative operating costs of different chilling systems [62].

which the flow (through flow) was in the same direction. If the cost of weight loss is also included in the calculations, then the relationship changes again. A 1% weight loss was worth 0.8 units on the comparative cost-scale.

There appears to be little published data on the measured or calculated rate of heat loss in poultry chilling. Mielnik et al. [40] used the temperature reduction during chilling and the weight of the carcass to calculate heat loss. They calculated that total heat loss during a 50 min chilling process was 93 kJ kg^{-1} for evaporative air chilling and 85 kJ kg^{-1} for air chilling.

Veerkamp and Hofman [63] produced equations for the rate of heat removal from a well-mixed immersion system, a less well mixed immersion system, a spray cooling system and a high velocity air system. However, the terms well mixed, less well-mixed and high velocity are not quantified in the paper.

3.2. Weight loss

From the moment a bird is slaughtered, it begins to lose weight by evaporation. In addition, to the direct loss in saleable meat, there are also secondary losses. Excessive evaporation during initial chilling and chilled storage produces a dark, unattractive surface on the carcass or portion. Either this has to be removed by trimming, or the meat is downgraded and sold at a reduced price. No systematic study of weight loss in current commercial chilling systems appears to have been published. The data that has been located is shown in Fig. 2 and Table 6. There are no strict internationally recognised technical definitions for the terms broiler, fryer, roaster and fowl found in the tables. Fowl is a generic term for a domesticated gallinaceous bird though to be descended from the red jungle fowl. Broilers, sometimes called fryers, are reared primarily for meat production and their age to market weight of 2.3–3.6 kg is typically 6–8 weeks. A roaster is a young meat-type chicken, usually 3–5 months of age, of either sex, that can be cooked tender by roasting, and usually weighing 2 kg or over.

Carcasses will lose weight during air chilling but gain in either a continuous water spray or immersion process. In air chilling, losses of 1–1.5% are common and can be up to 3% in badly designed equipment, while weight gains of 4–8% occur in immersion chillers [73]. In evaporative air chilling, losses are reduced to approximately 1%. Weight loss during evaporative (intermittent spays combined with air chilling) and air chilling at 3.0 ms^{-1}, 0 °C of 16 kg turkey carcasses was 1.1% [39]. Chilling in air at 0.2 ms^{-1} and 0 °C produced weight losses of approximately 2%. Veerkamp [69] states that using sprays at 5 and 15 min during air chilling would reduce weight loss to 0.8% in broilers and the application of 4–5 sprays in the chilling process would eliminate any loss. Simeonovov et al. [65] found average weight gains of 0.7–1.7% in the spray chilling of dressed broilers and up to 3.3% in immersion chilling. Countries that permit immersion chilling usually have established limits for water uptake. The limit in the EU is 4.5% [1].

3.3. Chilling time

The time taken to chill the carcass is a critical parameter in the design of any chilling system. The earliest publications on the rate of cooling emanated from Canada and USA and were concerned with still- or blast-air cooling systems [62]. In the 1930s and 1940s wet (water immersion) cooling found favour in USA. However, in the mid 1950s air and contact (plate) cooling of uneviscerated carcasses were the most common industrial practices in the UK. At that time, Hannan and Shepherd [74] carried out a comparison between typical dry, contact and wet cooling methods. Plate-contact cooling was found to be no faster than slow-moving air at 0 °C. Cooling times from 40 to 10 °C in the plate systems were approximately 5 h for a 2.5–3.5 kg uneviscerated carcass. In slow moving air, air blast

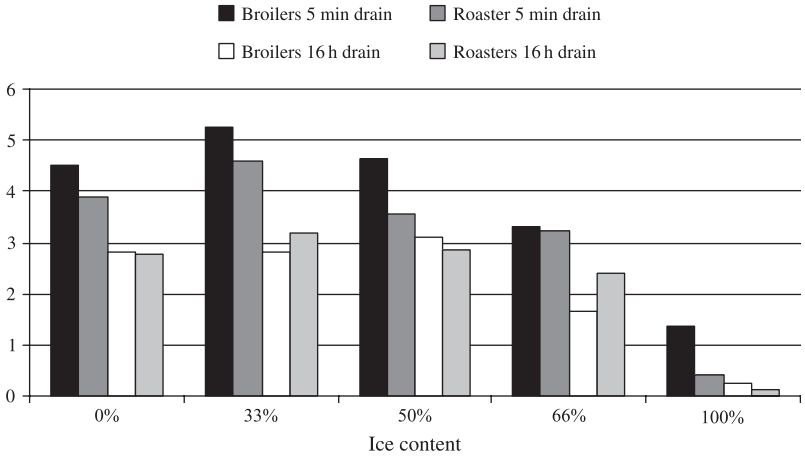

Fig. 2. Weight gain (%) of poultry after 8 h in ice/water immersion chilling systems then drained for 5 min or 16 h [64].

Table 6
Percentage weight change during chilling

Method of chilling	Details	Type of carcass	Weight (kg)	% Weight change	Ref.
Immersion	Two stage immersion chiller	Broiler		+7.4	[22]
	–	Broilers		+4 to 8	[73]
	–	Broilers		Up to +3.0	[65]
	2 h slush ice then ice packaged and held in room at 1.7 °C for 96 h	Fryers		+4.0	[66]
	4 h slush ice then ice packaged and held in room at 1.7 °C for 96 h	Fryers		+3.7	[66]
	24 h slush ice then ice packaged and held in room at 1.7 °C for 96 h	Fryers		+5.6	[66]
	0.5 h in still ice slush	Broilers	1.36–1.6	+2.0	[67]
	2 h in still ice slush	Broilers	1.36–1.6	+2.8	[67]
	23 h in still ice slush	Broilers	1.36–1.6	+5.3	[67]
	0.25 h in tumbling ice slush	Broilers	1.36–1.6	+4.8	[67]
	0.5 h in tumbling ice slush	Broilers	1.36–1.6	+11.7	[67]
	–	Chicken		+4.3	[68]
	–	Hens		+3.6	[68]
	–	Ducklings		+6.7	[68]
	–	Ducks		+6.1	[68]
	–	Turkeys		+5.6	[68]
	–	Geese		+7.3	[68]
Combined	Two stage immersion chiller plus air −7 °C, 3.5 ms^{-1}	Broiler		+5.5	[22]
	Ice packaged and held in room at 1.7 °C for 96 h	Fryers		+2.2	[66]
Spray	–	Broilers		−1	[73]
	Sprays at 5 and 15 min	Broilers		−0.8	[69]
	4–5 sprays	Broilers		0.0	[69]
	–	Broilers		+0.7 to 1.7	[65]
	With air at 0.5 ms^{-1}, 0.4 °C	Broilers	0.93	−0.2	[40]
	Sprays for 15 min then air −3 to −4 °C, 3 ms^{-1}	Broilers		+0.5	[70]
	With air at 3.0 ms^{-1}, 0 °C	Unwrapped Turkey	16 kg	−1.1	[39]
	With air at 0.2 ms^{-1}, 0 °C	Unwrapped Turkey	16 kg	−2.0	[39]
Evaporative	–	Broiler portions		−5	[71]
	Dipped in methyl cellulose before	Broiler	1.22	−1	[71]
	50 ml water placed in cavity before	Broiler	1.00	+1	[71]
Air	–	Broilers		−1 to −3	[73]
	0.5 ms^{-1}, 0.3 °C	Broilers	0.91	−2.0	[40]
	1 °C, 0.75 ms^{-1}, 91% RH 2 h post mortem	Broiler		−1.9	[72]
	1 °C, 0.75 ms^{-1}, 91% RH 4 h post mortem	Broiler		−2.55	[72]

(2.5 ms^{-1}) and an ice/water mix cooling times were 4.4, 3.1 and 2.1 h, respectively. In 1938, Cook and Sair [75] produced Eq. (1) that relates chilling time to carcass weight and air temperature:

$$T = -5 + 6.23 \log_{10}(t_p - t_a) + 1.156\,W \quad (1)$$

where T, time in hours to cool to 2 °F above the air temperature; t_p, the initial carcass temperature (°F); t_a, the air temperature (°F) and W, the weight of the bird in pounds.

The relationship was based on experimental results from a large number of birds, however, the air velocities, hanging details, etc. are not mentioned. At the time the carcasses would be uneviscerated so the equation is only of historic interest. However, since that time limited published data appears to have immerged on the relationship between carcass and environmental variables and chilling time. Data that has been located is shown in Tables 7–9.

4. Primary chilling methods

Immersion, spray (evaporative) and air are the three most common methods of chilling dressed poultry, a limited number of studies have looked at cryogenic coolants [57] but in 1982 it was reported that there had been little commercial adoption [37]. In 2005 the authors do not know of any

Table 7
Chilling times of poultry carcasses in immersion chilling systems

Carcass type	Weight (kg)	Chilling method	Temperature (°C)		Time (min)	Ref.
			Start	Finish		
Uneviscerated broilers	2.5–3.5	Immersion in ice/water at 0 °C	40	10	126	[74]
Broilers		Immersion 28 l min^{-1}	32	4	25	[64]
Broilers		Immersion free convection			About 40	[68]
Broilers		Water circulation, rate about 0.1 ms^{-1}			About 35	[68]
Broilers		Water circulation, rate about 5 ms^{-1}			About 32	[68]
Broilers	1.33	50:50 ice water		2–4	30	[76]
Broilers		Immersion chiller		<4.0	30–50	[77]
Broilers		Immersion chiller 50% methanol at −29 °C	38	4.0	35	[78]
Broilers	1.36–1.47	Immersion in ice water mix at 0 °C		4	80	[79]
Broilers		Immersion chiller, conventional counterflow	39.6	7	<90	[17]
Broilers		Paddle chiller		2.2	<60	[80]
Broilers		Static ice slush		4.2	60	[80]
Broilers		Static ice slush with air agitation		1.9	60	[80]
Roaster	2.3–3.2	Immersion in 33% ice immersion system			100	[64]
Roaster	2.3–3.2	Immersion in 50% ice immersion system			95	[64]
Roaster	2.3–3.2	Immersion in 66% ice immersion system			70	[64]
Roaster	2.3–3.2	Immersion in 100% ice immersion system			165	[64]
Broiler	0.9–1.4	Immersion in 33% ice immersion system			60	[64]
Broiler	0.9–1.4	Immersion in 50% ice immersion system			55	[64]
Broiler	0.9–1.4	Immersion in 66% ice immersion system			56	[64]
Broiler	0.9–1.4	Immersion in 100% ice immersion system			140	[64]
Broiler		Two stage immersion chiller		4	25	[22]
Broiler		Two stage immersion chiller plus air −7 °C, 3.5 ms^{-1}	4	−2	45	[22]
Broiler	0.9	0 °C slush ice, wrapped		4.5	95	[81]
Broiler	0.9	0 °C slush ice, unwrapped		4.5	50	[81]
Broiler	1.1	0 °C water, wrapped		4.5	105	[81]
Broiler	1.1	0 °C water, wrapped		4.5	60	[81]
Broiler	1.0	−5 °C brine, wrapped		4.5	70	[81]
Broiler	1.0	−5 °C brine, unwrapped		4.5	27	[81]
Broiler	0.9	−18 °C brine, wrapped		4.5	42	[81]
Broiler	0.9	−18 °C brine, unwrapped		4.5	24	[81]
Broiler	1.3	−29 °C brine, wrapped		4.5	35	[81]
Broiler	1.3	−29 °C brine, unwrapped		4.5	16	[81]
Fowl	2.0	0 °C slush ice, wrapped		4.5	190	[81]
Fowl	2.0	0 °C slush ice, unwrapped		4.5	90	[81]
Fowl	1.9	0 °C water, wrapped		4.5	195	[81]
Fowl	1.9	0 °C water, unwrapped		4.5	100	[81]
Fowl	1.6	−5 °C brine, wrapped		4.5	105	[81]
Fowl	1.6	−5 °C brine, unwrapped		4.5	38	[81]
Turkey	6.8	In drained ice at 0 °C	35	4.4	420	[82]
Turkey	6.5	In ice water at 0 °C	35	4.4	180	[82]
Turkey (16 week stags)		Immersion 40 min at 16 °C, 30 min 0 °C, air at 3 °C		5.0	300	[83]
Turkey (16 week stags)		Immersion 70 min 0 °C, air at 3 °C		4.8	300	[83]
Turkey (22 week stags)		Immersion 40 min at 16 °C, 30 min 0 °C, air at 3 °C		9.8	300	[83]
Turkey (22 week stags)		Immersion 70 min 0 °C, air at 3 °C		9.4	300	[83]
Turkey Stag	2.7	0 °C slush ice, wrapped		4.5	220	[81]
Turkey Stag	2.7	0 °C slush ice, unwrapped		4.5	95	[81]
Turkey Stag	2.7	0 °C water, wrapped		4.5	235	[81]
Turkey Stag	2.7	0 °C water, unwrapped		4.5	135	[81]
Turkey Stag	2.5	−5 °C brine, wrapped		4.5	165	[81]
Turkey Stag	2.5	−5 °C brine, unwrapped		4.5	55	[81]
Turkey Hen	5.3	−18 °C brine, wrapped		4.5	215	[81]
Turkey Hen	5.3	−18 °C brine, unwrapped		4.5	110	[81]

Table 7 (*continued*)

Carcass type	Weight (kg)	Chilling method	Temperature (°C)		Time (min)	Ref.
			Start	Finish		
Turkey Hen	5.3	−29 °C brine, wrapped		4.5	160	[81]
Turkey Hen	5.3	−29 °C brine, unwrapped		4.5	60	[81]
Turkey Tom	10.8	−29 °C brine, wrapped		4.5	205	[81]

commercial plants in the UK or EU that use cryogenics to chill poultry carcasses.

4.1. Immersion

In immersion chilling carcasses are moved through a tank or series of tanks containing chilled water or a mixture of ice and water. Some authors [27] contend that weight gain during immersion chilling is not a major factor in the popularity of this method. However, some early immersion chilling systems do appear to have been developed to maximise weight gain. Carcasses were immersed in water at temperatures above 12 °C, where they absorbed between 12 and 15% of their weight. They were then transferred to water at 1–2 °C to complete the chilling process. Nowadays, counter-current immersion chilling systems are used with a maximum water inlet temperature of 4 °C. Dwell-time and degree of water agitation are controlled to limit water absorption by the carcasses. Chilling rates in an immersion system are usually far faster than those achieved in air, with spray chilling producing times in between air and immersion methods.

Chilling rates in immersion systems are a function of the cooling medium used, its temperature, the size of the carcass being chilled and whether it is wrapped or unwrapped. Typical chilling times for a range of immersion systems are given in Table 7. The data from Esselen et al. [81] show that immersion in slush ice is far more effective than water immersion at the same temperature. This is to be expected as it takes in the advantage of the cooling capacity of melting ice. In all cases, unwrapped carcasses cooled far faster than those that were wrapped, the effect of wrapping being a doubling in the cooling time in some cases. These data also clearly demonstrate the effect of carcass size on cooling time, with unwrapped broilers cooling in 55–71% of the time required for unwrapped fowls under the same conditions. The time required to chill a 1 kg carcass to 4 °C

Table 8
Chilling times of poultry carcasses in spray/evaporative chilling systems

Carcass type	Weight (kg)	Chilling method	Temperature (°C)		Time (min)	Ref.
			Start	Finish		
Unwrapped broilers	0.93	Evaporative (spray) with air at 0.5 ms^{-1}, 0.4 °C	34.9	5.0	50	[40]
Broilers		Evaporative (spray) 15 l per bird		6	30	[84]
Broilers		Evaporative (spray) 12 l per bird at 0 °C	35	5	35	[85,86]
Broilers		Evaporative (spray) at 12 l per bird at 0 °C		7	35	[87]
Broilers		Evaporative (spray)	34.8	8.1	45	[88]
Broilers		Evaporative (spray)		12.0	27.5	[89]
Hens		Evaporative sprays for 15 min then air −3 to −4 °C, 3 ms^{-1}		<4.0	80	[70]
Broilers	0.80	Evaporative (spray) 100 l per bird at 2.5 °C	32	5	30	[90]
Broilers hung by wings	0.80	Evaporative (spray) 12 l per bird at 2.5 °C	30	13	30	[90]
Broilers hung by hocks	0.80	Evaporative (spray) 12 l per bird at 2.5 °C	30	9	30	[90]
Broilers	1.00	Evaporative (spray) 12 l per bird air 6 °C. 0.9 ms^{-1}	30	12	30	[90]
Broilers		Evaporative (spray, light) in spiral Ventstream	39.2	1.5	<90	[17]
Broilers		Evaporative (spray, moderate) in clipbar air chiller	38.3	4.4	<90	[17]
Broilers		Evaporative (spray, moderate) in standard Ventstream	39.6	3.0	<90	[17]
Broilers		Evaporative (spray, heavy) in standard Ventstream	35.1	5.7	<90	[17]
Broiler	1.22	True evaporative dipped in methyl cellulose before.	29	2	30	[71]
Broiler	1.00	True evaporative 50 ml water placed in cavity before.	26	1	29	[71]

Table 9
Chilling times of poultry carcasses in air chilling regimes

Carcass type	Weight (kg)	Chilling method	Temperature (°C)		Time (min)	Ref.
			Start	Finish		
Unwrapped broilers	0.91	Air chilling at 0.5 ms^{-1}, 0.3 °C	33.2	5.4	50	[40]
Uneviscerated broilers	2.5–3.5	Slow moving air 0 °C	40	10	264	[74]
Uneviscerated broilers	2.5–3.5	Air blast 2.5 ms^{-1}, 0 °C	40	10	186	[74]
Uneviscerated fowl	1.4	Still air at 1.7 °C		3.9	390	[91]
Uneviscerated fowl	2.3	Still air at 1.7 °C		3.9	480	[91]
Uneviscerated fowl	2.7	Still air at 1.7 °C		3.9	600	[91]
Uneviscerated cock	1.8	Still air at 1.7 °C		3.9	420	[91]
Uneviscerated cock	3.2	Still air at 1.7 °C		3.9	600	[91]
Uneviscerated cock	4.0	Still air at 1.7 °C		7	900	[91]
Uneviscerated fowl	1.8	Air at 1.7 °C, 2.5 ms^{-1}		3.9	260	[91]
Broilers	1.3	Air at −5 to 0 °C	30	4	90	[73]
Broilers		Air blast at −18 °C	38	<3.0	27	[92]
Broilers		Air blast at −29 °C	38	<3.0	23	[92]
Broilers		Air blast at −40 °C	38	<3.0	17	[92]
Broilers		Air 1 °C, 0.75 ms^{-1}, 91% RH	26.2	<4.0	150	[72]
Broilers		In wire baskets air −7 °C, 4.1 ms^{-1}		4	60	[93]
Broilers		Air standard Ventstream	35.1	7.0	<90	[17]
Broilers	1.25	Air at −12 °C		3.4	65	[56]
Broilers	1.25	Air at 0 °C		8.9	95	[56]
Broiler		Air 1 h at 5 °C then 0 °C		1	150	[94]
Turkey	6.5	In unevacuated bag in air blast at 1 °C	35	4.4	780	[82]
Turkey	6.2	In canvas shroud in air blast at 1 °C	35	4.4	520	[82]

ranged from 25 min in a medium at −5 or −18 °C, to approximately 55 min at 0 °C. Corresponding figures for a 1.56 kg bird were 38 and 95 min.

The percentage of ice used in slush ice systems has been shown to affect moisture absorption by the carcass as well as the cooling time. Mickelberry et al. [64] found that cooling time was at a minimum for an ice content of approximately 70% with the highest weight gain achieved at approximately 35% (resulting in a weight gain of 5.2 and 4.6%, respectively, for broilers and roasters). This suggests that in order to compare the performance of different slush ice systems the ratio of ice to water must be known.

Sivacheva et al. [68] concluded that a water circulation rate of 0.1 ms^{-1} was more than satisfactory in immersion chilling. In their opinion the trend to speed up circulation was not justified either economically or technologically. Their theoretical analysis of the heat transfer coefficient showed that in the case of immersion chilling it was the product thickness that mattered. They concluded that the intensification of water circulation would not greatly increase the heat transfer coefficient and, therefore, would not reduce the chilling time significantly.

4.2. Spray/evaporative

During spray chilling, water is sprayed onto carcasses as they are suspended in refrigerated air. The term 'spray' covers a number of different options and is sometimes referred to as 'evaporative air chilling' to further confuse matters. Typical chilling times for a range of spray and evaporative systems are given in Table 8.

It is thought that only one true spray chilling system, relying on large quantities of refrigerated water (12 l per bird) sprayed continuously on the carcasses has ever been installed commercially [87]. Experimental 'spray chilling installations, using very large volumes of refrigerated water produced microbiological results comparable with those obtained in well operated controlled immersion chilling systems' [30]. Other spray chilling systems rely on intermittent sprays, for example at five and 15 min after the start of air chilling, on four or five occasions during the whole chilling process [69]. The principle of the process is to increase the rate of evaporative heat loss and by replacing the water lost, reduce the overall weight loss. Although often called evaporative air chilling, it should not be confused with true evaporative chilling of poultry as described by Klose [71]. In his study, poultry carcasses were placed in a vacuum chamber and the cooling rates produced were similar to those achieved in immersion systems. However, the 5% weight loss that occurred was considered too high for industrial use. Spraying the carcass with a methylcellulose solution reduced the weight loss to 1%. Placing 50 ml of water at 1 °C in the cavity before chilling resulted in a 1% weight gain.

4.3. Air

In air chilling refrigerated air is blown over the carcasses. Due to the scale of production in most poultry slaughterhouses the dressed carcasses are normally conveyed continuously on rails through a room or tunnel. In large plants, the birds will be automatically transferred from the slaughter conveyer to the chill room system. In other plants, carcasses are manually hung on long rails (clip bars) that index through the chiller. As the required throughput increases there is a trend to move to much larger chill rooms and far more free space, above and below, the rails. This makes it far easier to clean the structure of the chill room and maintain the rail system. Chilling time and weight loss are a function of the environmental conditions within the chiller and the spacing between carcasses.

Typical chilling times for a range of air chilling systems are given in Table 9. Thomson et al. [58] quote Heimbach and Berner [93] who decreased chilling time 10–15% by increasing air velocity from 3.5 to 7.0 ms^{-1} at temperatures ranging from −10 to −40 °C. They reported a drop of about 10 °C in 20 min for non-packaged carcasses hanging in a chiller with air at −2 °C and a velocity of 2.5 ms^{-1}. Heimbach and Berner [93] also quote Vacinek [92] who reported no significant difference in the time required to chill chicken carcasses at air velocities of about 3.5 and 4.6 ms^{-1}. In an air-blast chiller, the times required to chill carcasses from 38 °C to below 3 °C at air temperatures of −40, −29 and −18 °C were 17, 23 and 27 min, respectively. Vacinek [92] also found that carcasses hung by the hocks in a vertical position generally cooled faster than carcasses in a horizontal position, hanging exposed a larger surface area for chilling.

4.4. Deep or super chilling

In general, poultry producers try to avoid surface freezing of the chicken carcass during chilling. This is mainly related to concerns of its affect on drip. However, there is published evidence that crust freezing may have no affect on meat quality and process known as deep or super chilling has been commonly utilised in USA. Carcasses are water chilled then put through an air freezer operating at −15 °C for approximately 30 min [29]. After packaging they are again placed in an air freezer to achieve the required meat temperature. The carcasses are stored and distributed at −1 to −2 °C. There is very little published data on the freezing point of poultry meat. It is generally recognised to be between −1.5 and −2 °C, though, as yet unpublished studies by the authors of this paper have measured a freezing point of approximately −1.3 °C in the deep breast of standard UK carcasses. However, in USA −2.2 °C is used [95] and a value as low as −2.8 °C has been quoted [96]. Legally in USA poultry meat kept above −3.3 °C can be marketed as fresh [52].

Studies carried out in the 1970s [92] showed that crust freezing poultry carcasses during chilling and then allowing the bird to equalise to approximately 4 °C did not produce any quality problems. Chilling a 1 kg carcass in air at −40 °C, 4.6 ms^{-1} for approximately 13 min resulted in an equalised (in an ice bath) meat temperature of 3.7 °C. There was no difference in taste panel scores for general acceptability, colour, juiciness, tenderness or flavour compared with chilled controls. No differences were also found in objective measurements of drip or shear force.

5. Discussion and conclusions

Primary chilling of poultry carcasses is carried out to maintain a safe product by reducing the temperature of the meat to lower the rate of growth of pathogenic and spoilage microorganisms. In general, primary chilling reduces the numbers and prevalence of pathogenic and spoilage microorganisms on poultry carcasses. There is also some evidence that chilling changes the relative numbers of different types of bacteria on the surface of poultry. Larger reductions in numbers of microorganisms are found when immersion chilling systems are used, especially if the water is chlorinated (a practice no longer permitted in the EU). Air chilling usually produces little if any change. From the published data, the adoption of air chilling in Europe does not appear to be based on any strong microbiological reasons.

There appears to be little published data that shows if different chilling regimes affect the flavour or colour of poultry meat. Ageing of poultry meat is not as long or as critical as in red meat but very rapid chilling can cause texture problems unless electrical stimulation is used.

Reducing evaporative weight loss is critical to the economic success of a poultry chilling operation. Immersion and spray chilling can substantially reduce the loss and can result in a weight gain. No systematic studies appear to have been carried out to relate air chilling conditions to weight loss. Only one paper on the comparative costs of different chilling operations has been located and little data is available on heat load profile during chilling.

Overall there is a dearth of published data relating the rate of temperature reduction in different parts or poultry carcasses to carcass weight, dimensions and chilling conditions.

With single processing lines commonly processing 10,000 birds per hour and more there is increasing interest in optimising poultry chilling systems. Companies are after shorter chilling processes, minimum weight loss, lower energy consumption and lower capitol costs. This all has to be achieved without any reduction in product safety or quality. In many ways immersion chilling meets many of these objectives and continues to be the preferred system in many countries. However, throughout the EU companies rely on air chilling systems for poultry that is to be sold as a ‘fresh’, chilled product and feel the market will not accept a full return to immersion techniques. Possibly the way ahead is to produce multi stage systems incorporating

immersion or crust freezing into the initial stages. Currently the lack of real data on the effect of conditions on chilling rates, weight loss and quality restrict progress.

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