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Immersion Vacuum-Cooling as a Novel Technique for Cooling Meat Products: Research Advances and Current State-of-the Art

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Abstract: In order to achieve a rapid cooling rate and to increase the industrial yield of the products without compromising their quality attributes, immersion vacuum-cooling (IVC) is now widely applied for cooling of both small and large food items. However, the lower cooling rate compared with vacuum-cooling has initiated numerous studies to improve this technique. Substantial efforts, such as combination of IVC with other cooling methods, using different initial water temperatures, or employment of agitation during IVC, have been made to optimize cooling parameters while also maintaining quality properties and complying with strict food safety requirements. This review presents and discusses the IVC evolution and recent developments directed at the ready-to-eat meat products industry. The principle of IVC and its applications are discussed first. Then future prospects and suggestions are covered, especially for the cooling of ready-to-eat meat products.

Keywords: immersion vacuum-cooling, cooling rate, cooling loss, meat products

Introduction

Time saving and convenient ready-to-eat food products are becoming increasingly popular because of the increase in "money-rich, time-poor" individuals (Mendonca 2010; Feng and others 2013a; Feng and Sun 2014). The increasing availability of processed foods is enabling this trend. Cooking is a traditional, important process applied to some foods for many reasons, including the reduction of microbial food safety risks. However, it does not destroy all the microorganisms: some bacterial spores and thermoduric vegetative cells can survive, which then contribute to the spoilage of the cooked products, especially if the cooked foods are stored for extended periods of time before consumption. Rapid cooling is an efficient measure taken to avoid microorganism growth or recoveries (Aggelis and other 1998). To ensure the safety of cooked meat products during distribution and display, cooked meat portions (2.5 kg, 10 cm thickness) should complete cooling in 150 min from core temperature of 74 to 10 °C in Ireland (Anonymous 2006). For sausages, a small sausage (diameter: 1.6 to 2.8 cm) should achieve cooling in less than 5 to 10 min from 55 to 10 °C, and in less than 15 to 20 min for large sausages (diameter: 2.8 to 4.0 cm) (USDA 1999; Feng and Sun 2014). Traditional cooling methods are unable in many cases to meet the aforementioned guidelines, mainly because of the poor thermal convection between meat and cooling medium as well as a low conduction in large-dimension meat products (Sun and Zheng 2006; Drummond and Sun 2012; Feng and others 2013a). Based on an evaporative cooling principle, vacuum-cooling (VC) can achieve cooling in an extremely short time (Brosnan and Sun 2003; Ozturk and Ozturk 2009; Feng and others 2012b; Zhang and others 2013) and thus ensure products safety before consumption (McDonald and Sun 2000; McDonald and others 2000; Drummond and Sun 2008a; Drummond and others 2009; He and others 2013). However, the high cooling losses during cooling procedure, high costs, and hard surface appearance after VC have limited its widespread use to cool meat products. From the viewpoint of economy, a small decrease in yield may be significant for the meat industry, as products are cooked and cooled in large batches at a time and are priced according to their weight (Feng and others 2012a).

Immersion vacuum-cooling (IVC) can achieve a high cooling rate compared with conventional cooling methods (Schmidt and others 2010; Feng and others 2012a), with a comparably lower cooling loss compared with VC (Feng and others 2012a, 2013a). Increased competitiveness coupled with food safety concerns has caused researchers to refine this technology. This includes combination of IVC with other cooling methods (Dong and others 2012; Chen 2014; Du and others 2014), accurate pressure reduction rate control (Feng and others 2013a), employment of agitation during IVC (Feng and others 2013a, 2014a; Feng and Sun 2014), choosing different condensing temperatures (Feng and Sun 2014), and using water with different initial temperatures (Feng and others 2013a; Feng and Sun 2014; Liu and others 2014). All these research studies accentuate an unyielding interest in the improvement of IVC as an efficient cooling method that can be used to apply to the different types of cooked meat products. Therefore,

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the aim of this paper was first to comprehensively review the evolution of IVC. Then the latest applications focusing on large and small cooked meat products are presented. Future trends in relation to IVC of cooked meat products are also discussed.

Evolution of IVC

In order to meet the requirements of a high cooling rate with a comparably lower cooling loss, several approaches have been exploited to improve VC procedures. IVC was demonstrated to be the most satisfactory one among all proposed methods (Feng and others 2012a). Houska and others (2003) first investigated VC of different kinds of small cooked beef pieces (between 0.1 and 0.6 kg) in cold water (around 20 °C), pre-cooled soup, and hot bouillon (soup), respectively. Results showed that cooling losses varied in accordance with different soups used for IVC processing. Beef muscles from 4 different carcass parts were employed. Cooling losses were significantly lessened in this way and even weight increased in the injected sirloin cuts (6.9%) (Houska and others 2003). This satisfactory outcome stimulated researchers to apply IVC to larger cooked meat items. Consequently, VC of pork hams (2.2 ± 0.2 kg) and beef joints (between 1.0 and 4.3 kg), together with their cooking solutions, were investigated by Cheng and Sun (2006a) and Drummond and Sun (2008a), respectively. Cooling losses were reported to be 7.0% for the pork ham (Cheng and Sun 2006a) and 5.3% for the beef joint (Drummond and Sun 2008a).

In the experiment by Houska and others (2003), the solution used for IVC was colored and color was observed in the interior meat pores after slicing. This indicates that solution was infiltrated when the vacuum broke. Accordingly, different pulse cycles (vacuum break times until chamber pressure got to atmosphere before the end of IVC) were used during the IVC procedure. Small pieces of pork cutlet (0.3 ± 0.1 kg) and beef sirloin (0.9 ± 0.1 kg) (Houska and others 2005) as well as large pork hams (2.2 ± 0.2 kg) (Cheng and Sun 2006b) were immersion vacuum-cooled using different cycles. The effects of cycles during IVC on meat cooling losses were not significant in the experiments conducted by Houska and others (2005) ($P > 0.05$), whereas IVC of large pork hams using 4 cycles significantly reduced cooling losses from 7.0% (one cycle) to 4.9% ($P < 0.05$) (Cheng and Sun 2006b). The different viscosity between water and sauces used in the various experiments contributed to these distinct observations. Subsequently, further studies on immersion-cooking followed by 3 pulsed cycles of IVC (ICK–PIVC), and combined immersion-cooking and VC with vacuum-impregnation (ICK–VC–VI) were carried out by Schmidt and Laurindo (2014). Cooling loss of ICK–PIVC achieved the lowest cooling loss (2.8%) in comparison with that of ICK–IVC (4.8%), ICK–VC (11.6%), and ICK–VC–VI (11.5% to 11.7%).

Combining IVC with VC was also developed in recent years (Dong and others 2012; Hu and others 2012; Chen 2014; Du and others 2014). Pork (1.5 kg) was first vacuum-cooled to the intermediate temperature (25 °C) and then immersion vacuum-cooled to the final temperature (10 °C) using chilled cooking solution (10 °C) (VC–IVC) (Dong and others 2012). The cooling rate of VC–IVC (0.73 °C/min) was significantly higher than that of IVC (0.44 °C/min), with the cooling loss (6.7%) significantly higher than that of IVC (6.5%) ($P < 0.05$) (Dong and others 2012). In the experiments performed by Hu and others (2012), chicken (1.0 ± 0.1 kg) cooled using IVC followed by immersion cooling (IVC–IC) displayed a considerably higher cool rate (1.54 °C/min) than that of air-blast-cooling (0.62 °C/min). Experiments conducted by Du and others (2014) show that cooling chicken legs (0.1 kg) using VC–IVC presented the lowest cooling time from 72 to 10 °C (31 min), compared with 78 min for VC and 100 min for IVC. However, the average cooling loss of VC–IVC cooled chicken legs was 0.05%. Samples cooled by IVC increased to 0.1% after the cooling procedures (Du and others 2014).

Both Drummond and others (2009) and Cheng and Sun (2006a) mentioned that the heat transfer at the later stage of IVC should be improved in order to shorten the cooling time of IVC. A mechanical agitation employed in IVC processing was recommended to enhance the heat exchange by promoting circulation in the container (Cheng and Sun 2006a; Drummond and others 2009). To this end, the agitation was used in both IVC of large pork ham (Feng and others 2013a) and of sausages (Feng and Sun 2014; Feng and others 2014a). It was reported that cooling time to 4.6 °C was reduced by 47.4% after employing agitation during IVC of large pork ham (3.8 ± 0.2 kg) (Feng and others 2013a). Regarding the sausages, the cooling time for sausages stuffed in natural casings was significantly reduced from 76.5 (min) to 45.3 (min) after employment of agitation ($P < 0.05$), whereas no significant differences were observed in that of stuffed in artificial casings ($P > 0.05$) (Feng and others 2014a).

The pressure reduction rate in studies carried out by Cheng and Sun (2006a, b) and Drummond and Sun (2008a) were controlled in a manual or indirect way. The pressure drop rate thus greatly depended on the operator's experience and so resulted in poor repeatability for each experiment. Accurate pressure reduction rate control can prevent a large amount of vapor generated and remaining in the vacuum chamber which adversely influences the pressure drop rate. Furthermore, accurate pressure drop control reduces the burst incidence of packaged foodstuffs, where some vapor can escape from the interior of packaged food products. Pressure drop rate, which was automatically and accurately regulated by an electronic valve controlled by LabView software (v4.1, Notional Instruments), was thus employed to cool pork ham (Feng and others 2013a) and sausages (Feng and Sun 2014; Feng and others 2014a, b). A shorter IVC time to 4 °C (185.2 min) was obtained when a lower pressure reduction rate [L 6000 (Pa/min)] was employed, although the difference was insignificant at a 5% level (Feng and others 2013a). The similar phenomenon occurred with IVC of sausages stuffed in natural hog casings (Feng and Sun 2014; Feng and others 2014a).

The effects of condensing temperature on VC have been investigated by Wand and Sun (2004). There was only a 13-min reduction when a condenser of 2.5 °C was employed for VC large cooked meat joints (130 kg). For IVC processing, the average cooling time of IVC of natural casing-stuffed sausage was reduced from 57.0 min (condensing temperature: 8 °C) to 29.2 min (condensing temperature: −4 °C), provided the same other cooling conditions were employed [initial water temperature (IWT): 46 °C; pressure drop rate: 7500 Pa/min; agitation speed: 450 rpm] (Feng and Sun 2014). This is again due to the extensive water spillage and liquid accumulation inside the chamber, which always occurs under a rapid pressure drop rate. The large amount of vapor generated with the high pressure drop rate leads to the vapor being condensed on the cooler internal surfaces and evaporated again under a lower pressure (Feng and others 2013a). Consequently, a vapor-condensing unit was recommended for the IVC system, particular for the IVC of small foodstuffs.

Principle and Processes of IVC

IVC involves in VC of a hot food product while being immersed in a surrounding liquid (Drummond and Sun 2008b; Drummond

and others 2009). Unlike VC, the principle of IVC is based on a combination of water evaporation, thermal conduction, and thermal convection (Cheng and Sun 2006a). According to the chamber pressure, the whole IVC cooling procedure was divided into 3 stages by Cheng and Sun (2006a): violent, strong, and simmering boiling phases. At the violent stage, the water evaporation occurs in both meat cores and the surrounding water. When water evaporates, it absorbs the necessary latent heat from its surrounding for phase change and so cooling is achieved (Feng and others 2012a). It mainly applies to the products that contain a porous interior structure. At the later stage of IVC, the rate of evaporation greatly recedes and heat conduction within the meat and convection from the surface are then increasingly relevant and may even control the entire later stage of IVC processes (Feng and others 2012a). To this point, enhancing the heat transfer, especially at the bottom of the container, is an important approach to increase the cooling rate.

With regard to the operation of IVC, the cooling rate should be carefully adjusted in order to prevent violent water spillage (Feng and others 2013a) and to promote a stable evaporation rate (Drummond and Sun 2012). If pressure drops drastically, there will be a large amount of vapor generated and staying in the chamber (if not evacuated immediately), which increases the vacuum pump load, prevents further pressure reduction, and negatively influences the cooling rate. An optimal volumetric displacement within a certain pressure range during IVC has been proposed to be an effective way to reduce violent spillage (Song and others 2015). The best volumetric displacement was suggested to be 0.0012 m^3/s when the pressure was between 10000 and 2000 Pa (Song and others 2015). As the principle of IVC is based on water evaporation, thermal conduction, and convection, the size of samples greatly influences the cooling rate of IVC (Drummond and Sun 2008a). The effect of increasing pressure drop rates is gradually diminished with an increase of size (Drummond and Sun 2012). In order to comply with food guidelines to ensure the quality of a product, a slower cooling rate has been suggested for smaller products, whereas a higher cooling rate has been recommended for larger products (Drummond and Sun 2012).

During IVC processing, the quantity of water added into the container should be kept to a minimum. Compared with the experiments by Schmidt and others (2010), the cooling time in the experiments of Schmidt and Laurindo (2014) was reduced from 3.5 times of VC time to 2 times of VC time. The smaller amount of water used in experiments by Schmidt and Laurindo (2014) contributes to this phenomenon. A large quantity of water will generate more vapor, which may aggravate the cooling load for IVC systems. Furthermore, a higher water level also negatively affects the thermal exchange from the bottom to the surface of the water level.

Applications of IVC

To date, IVC has been successfully applied to various foodstuffs, especially cooked meat products. Table 1 summarized this for different types of meat products.

IVC of large-size meat products

During the past few years, IVC has become an innovative rapid cooling technique, and it has been applied to various large meat products. IVC offers a rapid cooling rate over the conventional cooling techniques, and it offsets a higher cooling loss that always occurs with VC (Cheng and Sun 2007).

The IVC of pork ham (2.2 ± 0.2 kg) has been extensively studied by Cheng and Sun (2006a, b). Cooling loss of IVC was reduced to 7.0%, which was nearly half of that of VC (13.7%) (Cheng and Sun 2006a). Accordingly, the Warner Bratzler shear (WBs) force, which was used to measure the tenderness of the products, displayed a lower value (28.1 N) for IVC samples than for VC samples (36.1 N) (Cheng and Sun 2006a). This indicates that the sample became more tender in the IVC process, which is due to the meat surface kept moist continually, and it shows a lower cooling loss (Cheng and Sun 2006a). The pressure, when broken at the end of the procedure, was demonstrated to drive some of the surrounding liquid into the interior of meat, alleviating the cooling loss and tenderizing the meat (Houska and others 2003). The IVC samples presented a lower redness ($a^\star = 9.2$) than VC samples ($a^\star = 11.8$), which again is attributed to the higher water content in IVC and which dilutes the concentration of meat pigments (Cheng and Sun 2006a; Feng and others 2012a). The effects of using different pulse cycles (1, 4, and 8) during IVC on cooling parameters and quality attributes of pork ham (2.2 ± 0.2 kg) were investigated by Cheng and Sun (2006b). All samples and variables of processing (pulse cycles) and quality characteristics were evaluated by principal component analysis (PCA). Pork ham cooled by IVC with 4 and 8 pulse cycles located together on the negative side of the first component (PC1) (Figure 1), where water holding capacity (WHC), water content, and product yield were observed. This means that 4 and 8 pulse cycles were positively correlated to WHC and water content and yield, whereas one pulse cycle is mainly responsible for the high WBs, chewiness, and hardness values (Cheng and Sun 2006b). Pork ham cooled by IVC with 4 and 8 pulse cycles is located at the same part in the plot (Figure 1), indicating the influences of the pork ham treated by 4 and 8 pulse cycles on processing and quality attributes were similar.

The state of water, bound water, immobilized water, and free water, during IVC of water-cooked pork (1.5 ± 0.1 kg) was monitored using low-field nuclear magnetic resonance (LF-NMR) (Dong and others 2011). Three different peaks (T_{2b}, T_{21}, and T_{22}) were detected (Dong and others 2011). T_{2b}, whose transverse relaxation time was 0 to 2 ms, represented the bound water that combined closely with polar groups on the surface of muscle protein molecules (Li and others 2014). T_{21}, with transverse relaxation time of 9 to 60 ms, stood for immobilized water that captured within the myofibril (Pearce and others 2011). T_{22}, the transverse relaxation time which was 100 to 400 ms, associated with free water that was located between fiber bundles and the inter-myofibrils (Shaarani and others 2006). The peak ratio of T_{21} for IVC (94.1 ± 0.1%) was significantly lower than that for VC (95.5 ± 0.6%) ($P < 0.05$), whereas the peak ratio of T_{22} for IVC (2.4 ± 0.4%) was significantly higher than that for VC (1.2 ± 0.5%) ($P < 0.05$) (Dong and others 2011). These findings indicate that the free water in meat during IVC procedures increased, whereas the ratio of the immobilized water declined (Dong and others 2011). As depicted in Figure 2, the signal of T_{2b} for VC samples weakened and the bulk NMR T_2 relaxation decay curve moved backward, which illustrates that the capability of meat molecules to capture the bound water and immobilized water lessened and the water's degree of freedom increased during the VC procedure (Dong and others 2011).

The effects of agitation (1002 rpm), pressure reduction rates (6000 and 10000 Pa/min), IWTs (7 and 20 °C) (Feng and others 2013a), and increment of food loads on IVC of cooked pork ham (3.8 ± 0.2 kg) (Feng and others 2012b) were also investigated. The cooling time (to 4.6 °C) was markedly decreased by 47.4% after employing agitation (Feng and others 2013a).

Table 1–Summary of applications of IVC to different types of meat products

Methods	Meat type	Meat weight (kg)	Results	References
IVC	Large pork ham	3.8 ± 0.2	Cooling time decreased by 47.4% using agitation in IVC	Feng and others (2013a)
	Two large pork ham	3.8 ± 0.2	Cooling 2 hams simultaneously did not affect cooling parameters and quality attributes	Feng and others (2012b)
	Large pork ham	2.2 ± 0.2	Much more tender; a lower redness; IVC cooling loss ≈ 1/2 VC cooling loss	Cheng and Sun (2006a)
	Pork	1.5 ± 0.1	Free water increased during IVC	Dong and others (2011)
	Small beef piece	0.1 to 0.6	Weight increase if meat with less collagen fibers	Houska and others (2003, 2005)
	Sauced chicken	1.0	Oxidations aggravate using IVC	Ren and others (2014)
	Sausage	0.072	Final temperature can reach 4.3 °C; better appearance for IVC; IVC cooling time ≈ 1/4 VC cooling time (to 10.4 °C)	Feng and others (2012c)
	NCS; ACS	NCS: 0.08; ACS: 0.04	Cooling time of IVC of NCS reduced using agitation; no significant differences observed in relation to cooling time of IVC of ACS before and after using agitation	Feng and others (2014a)
IVC with different IWTs	Large pork ham	3.8 ± 0.2	A shorter cooling time obtained with IWT of 7 °C	Feng and others (2013a)
	Cooked lamb	1.0 ± 0.3	Cooling losses was lower using IWT of 90 °C	Liu and others (2014)
	Sausage	0.08	Interactive effects caused by IWT and pressure drop rate positively affected hardness ($P < 0.05$)	Feng and Sun (2014)
PIVC	Large pork ham	2.2 ± 0.2	4 and 8 cycles had a similar effect; 4 and 8 pulsed cycles positively influenced WHC, water content and yield	Cheng and Sun (2006b)
	Small beef sirloin	0.9 ± 0.1	The effects of cycles were insignificant	Houska and others (2005)
ICK and PIVC	Chicken breast	0.2 to 0.3	ICK - PIVC showed the lowest total loss (2.8%)	Schmidt and Laurindo (2014)
IVC with DCT	Sausage	0.08	Condensing temperature linearly and significantly influence cooling time ($P < 0.001$)	Feng and Sun (2014)
IVC with DPD	Large pork ham	3.8 ± 0.2	A shorter cooling time observed using LA 6000 Pa/min; higher textural values obtained under 7 °C with LA 10000 Pa/min	Feng and others (2013a)
IVC with DWL	Sausage	0.072	A shorter cooling time obtained using LWL; water temperature differed with different positions of water level	Feng and others (2012d)
IVC and VC	Plain chopped pig's trotter	1.4 ± 0.03	A lower loss (3.4 ± 0.4%) and a higher springiness (1.03) obtained when intermediate temperature set at 30 °C	Chen (2014)
IVC and WI	Chicken	1.0 ± 0.1	IVC - WI cooling rate ≈ 2.5 AB; low cooling loss	Hu and others (2012)
VC and IVC	Pork	1.5 ± 0.1	VC - IVC cooling rate (0.73 °C/min) > IVC (0.44 °C/min); VC - IVC cooling loss ≈ 1/2 VC cooling loss	Dong and others (2012)
	Chicken legs	0.1	VC - IVC cooling rate (2.2 °C/min) > VC (0.8 °C/min); stable pH after 7 d cold room storage	Du and others (2014)
ICK and IVC	Chicken breast	0.1 to 0.2	A lower cooling loss and much more tender	Schmidt and others (2010)

DCT, different condensing temperature; DPD, different pressure drop rate; DWL, different water level; ICK, immersion cooking; IVC, immersion vacuum-cooling; IWT, initial water temperature; LA, linear pressure drop rate with agitation; NCS, natural casing sausage; ACS, artificial casing sausage; PIVC, pulsed immersion vacuum-cooling; VC, vacuum-cooling; WI, water immersion.

Nevertheless, the cooling time spent to cool the meat pieces from 72 to 10 °C was on average about two-thirds of the total cooling time (to 4.6 °C). This means that the later period of cooling time (from 10 to 4.6 °C) is still a slow stage in this case (Feng and others 2013a). As for using the different IWTs during IVC, a shorter cooling time was observed when water with a lower initial temperature (7 °C) was used, which may again be due to the larger amount of vapor generated in the water with a higher temperature (20 °C) (Feng and others 2013a). In addition, a fat layer at the surrounding liquid surface was noticeably observed when using the water with the higher IWT. Such layer may hinder vapor to escape and may probably result in a longer time. Moisture and protein contents, WHC, and WBs values showed insignificant differences ($P > 0.05$) between IVC samples cooled using

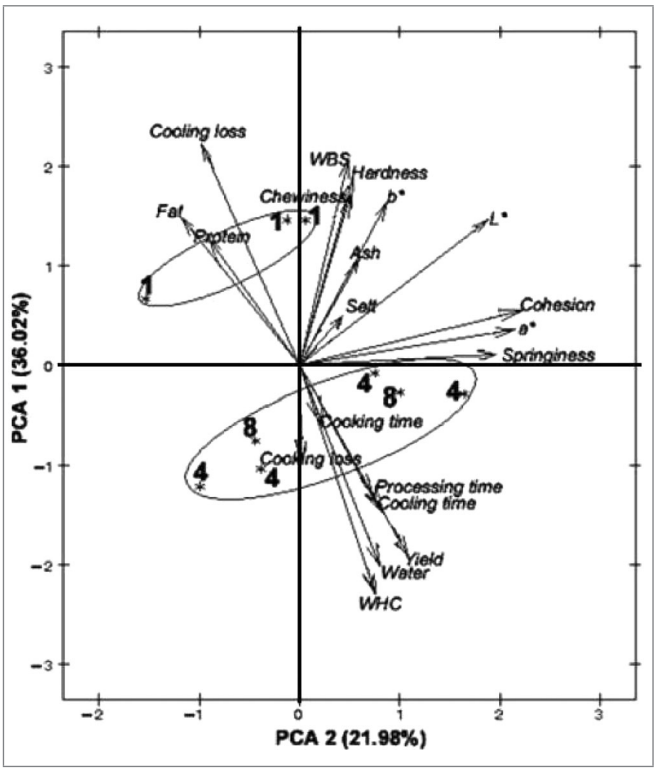

Figure 1–PCA of quality and cooling attributes of pork ham treated with different pulse cycles during IVC (Cheng and Sun 2006b).

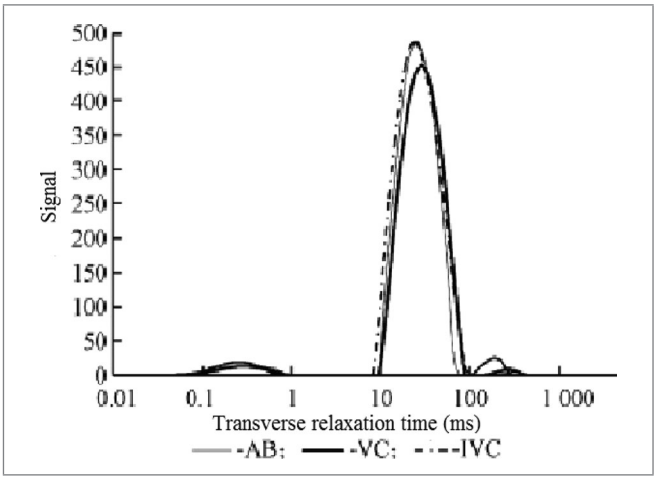

Figure 2–Distribution of T2 relaxation time for the water-cooked pork cooled by different cooling methods (Dong and others 2011).

different IWTs (Feng and others 2013a). The effects of different initial pure water temperatures (0, 25, and 90 °C) on IVC of cooked lamb (1 ± 0.3 kg) was also evaluated by Liu and others (2014). The cooling losses of cooked lamb after IVC using IWT of 90 °C (increase 5.3 ± 0.3%) was reported significantly lower than that using IWT of 0 °C (decrease 2.6 ± 0.2%) ($P < 0.05$), contrary to what Dong and others (2011) had stated. The authors explained that the pure water seeped into the pores much easier when the pressure recovered to atmospheric, compared to the water used after cooking. The cooking water contained salt, which may lead to a decrease of available proportional porosity (Liu and others 2014). More experiments need to be conducted to confirm this observation.

It was figured out that the effects of different pressure reduction rates [linear pressure drop rate (Pa/min) with agitation (LA) 6000 compared with LA 10000] on quality attributes of pork ham varied in accordance to different IWTs used (Feng and others 2013a). For instance, samples obtained higher hardness, gumminess, and chewiness values under 7 °C IWT with LA 10000 than that with LA 6000. However, samples cooled under 20 °C IWT with LA 6000 showed higher texture parameter values (hardness, chewiness, springiness, and cohesion) than that with LA 10000 (Feng and others 2013a). The authors attributed these observations to the positive interactive effects caused by IWT and pressure reduction rates. Likewise, the inherent textural properties variability may also be the reason for this phenomenon.

From a commercial point of view, cooling in large batches is preferable since it not only reduces time and, subsequently, increases product output, but also reduces energy consumption (Feng and others 2012b). If no negative effects are seen on ham quality, then IVC with increased loads are beneficial for commercial utilization. Subsequently, 2 large pork hams (3.8 ± 0.2 kg for average weight) were immersion vacuum-cooled simultaneously (Feng and others 2012b). There were no significant differences between cooling 2 hams and a single piece ($P > 0.05$) in terms of cooling time, moisture content, WHC, hardness, gumminess, lightness, and redness. The differences in relation to cooling time to the final temperature of 4 °C was insignificant ($P > 0.05$) (Feng and others 2012b). This may be because of the available surrounding liquid for cooling the ham was not changed when cooling load increased (Feng and others 2012b).

Chen (2014) investigated IVC of plain chopped pig's trotter (1.4 ± 0.03 kg). The results showed that it took approximately 160 min for IVC of samples from 72 to 10 °C, but the sample was less brittle. This may be due to the long-time immersion in water and softening the meat products. Hence, samples were first immersion vacuum-cooled to intermediate temperature (IT: 25, 30, and 35 °C) and then vacuum-cooled to ultimate temperature of 10 °C. Satisfactory results were obtained when the intermediate temperature was set at 30 °C, with a lower loss (3.4 ± 0.4%) and a higher springiness (1.03). Combining IVC with other cooling methods to cool meat products has also been documented by Dong and others (2012). Unlike the previous combination (Chen 2014; Hu and others 2012), meat was first vacuum-cooled to 25 °C and then immersion vacuum-cooled using chilled cooking solution (10 °C) to a final temperature of 10 °C (Dong and others 2012). The results displayed that the cooling rate (0.73 °C/min) was significantly higher than that of IVC (0.44 °C/min), whereas its cooling loss (6.7%) was nearly half of that of VC (11.8%). Comparing the results of Chen (2014) and Dong and others (2012), the total cooling times were about 80 min (IT: 25 °C), 57 min (IT: 30 °C), and 49 min (IT: 35 °C) for the IVC–VC processes (Chen 2014), whereas around 98 min (IT: 25 °C) for VC–IVC. The cooling loss for IVC–VC group (IT: 25 °C) was 2.5% (Chen 2014), compared with 6.7% for VC–IVC combination (Dong and others 2012). According to the simulation developed by Drummond and Sun (2012), a combination of IVC followed by VC was recommended from process efficiency and safety points of view. This statement is consistent with the studies carried out by Hu and others (2012), where the cooling rate of IVC–WI (1.54 °C/min) of chicken (1 ± 0.1 kg) was approximately 2.5 times that of air-blast-cooling (0.62 °C/min). The weight even increased by 6.5% after cooling (Hu and others 2012). As a higher cooling loss associated with a higher pressure drop rate (Huber and Laurindo 2006; Cheng and Sun 2007; Jackman and others 2007), a comparable lower pressure

drop rate during IVC (to avoid too much water spilling out of the container) can considerably reduce the cooling loss (Drummond and Sun 2008a, 2008b, 2012; Drummond and others 2009; Cao and others 2014). On the other hand, thermal conduction and convection prevailed at the later stage of IVC (after 25 °C) and thus controlled the whole cooling process (Drummond and Sun 2012). This phase is more relevant to safety risk, and the cooling rate in this stage needs to be accelerated (Drummond and Sun 2012; Hu and others 2012). As a result, IVC–VC was more reasonable to achieve a higher cooling rate with a comparably lower cooling loss (Drummond and Sun 2012).

IVC of small-sized meat products

Although IVC offers greater advantages with larger products than smaller products, using this technology on smaller products allows for the study of how other food systems respond to this process (Feng and Sun 2014). Compared with the aforementioned large meat joints, small products can be cooled much faster, and thus it increases product throughput and reduces cold room occupation (cooling) prior to storage. Subsequent chilled storage of cooked small foodstuffs throughout distribution and display is also important for quality purposes, and it is crucial to insure food safety (Feng and Sun 2014; Feng and others 2014c).

As the first successful application of the IVC procedure a range of different types of small cooked beef pieces (0.1 to 0.6 kg) were worked with Houska and others (2003, 2005). Results showed that meat that contains less collagen fibers, such as round beef cuts, gained more weight after VC (Houska and others 2003). It was explained that meat with collagen fibers contains fewer pores, which limits the water evaporation and so reduces the cooling loss.

IVC of chicken has been intensively studied as chicken breasts (0.1 to 0.3 kg) (Schmidt and others 2010; Schmidt and Laurindo 2014), sauced chicken (Ren and others 2014), and chicken legs (0.1 kg) (Du and others 2014). Schmidt and others (2010) integrated cooking and cooling processing to cook and cool chicken breast cuts in the same vessel, which reduces processing time and product manipulation. Water immersion-cooking followed by IVC (ICK–IVC) was regarded as an efficient alternative that can lower the cooling loss (3%), maintain the moisture of the product (70 g of water/100 g of sample), and tenderize the meat product (WBs force: 24.7 ± 2.9 N).

The effects of IVC of sauced chicken (1.0 kg) on quality and cooling attributes were investigated by Ren and others (2014). Oxidations in IVC and VC cooled samples were greater than that of natural cooled samples, which may be due to the generated or enlarged pores during VC or IVC processing which increased the surface area that contacted with oxygen (Ren and others 2014).

Du and others (2014) reported that the cooling rate of VC–IVC (2.2 ± 0.1 °C/min) was much faster than that of VC (0.8 ± 0.1 °C/min) when cooling a chicken leg. This is contrary to the previous statement where cooling rate of VC (1.3 ± 0.0 °C/min) gave a higher value than that of the VC–IVC group (0.7 ± 0.0 °C/min) when cooling large water-cooked pork (Dong and others 2012). The smaller size, coupled with the exterior skin, may explain this disagreement (Du and others 2014). The skin hindered the water evaporation and thus decreased the cooling rate. Furthermore, the chilled water was more readily impregnated into the core of small chicken leg in comparison to the large pork piece when vacuum broke, thus decreasing the temperature in the meat core (Du and others 2014). The pH was also tested during 7 d of vacuum-packaged cold room storage (4.0 ± 0.5 °C). The evolution of pH in samples cooled by different cooling methods was gentle, slightly increasing from 6.7 to 7.0 (Du and others 2014). The free amino acid generated by proteolysis may be the reason for this observation (Du and others 2014).

As aforementioned, the application of IVC is limited to porous products. If packaged, the packaging material should be perforated or permeable to allow vapor to easily escape from the product so that chilling can occur (Feng and Sun 2014; Feng and others 2014a, b). For foodstuffs like sausages, which have the unique characteristic of being *packaged* in permeable casings, made from either natural or artificial materials, there is an increased risk of the casing bursting when a high pressure drop rate is applied in the IVC process. The porosity and permeability of packaging material then become important parameters for their suitability with this cooling method.

Sausage can be regarded as a comminuted meat encased in a natural (or artificial) permeable membrane (casing) (Savic and Savic 2002) The feasibility of using IVC and VC to cool cooked sausages (made from natural hog casings, 0.072 kg) was first investigated by Feng and others (2012c). Results revealed that the lowest final temperature achieved by VC samples was about 10.4 °C, whereas IVC samples reached approximately 4.3 °C (Feng and others 2012c). The average cooling time for IVC to 10.4 °C (23.1 min) was only a quarter of that of VC (95.7 min), though the pressure drop rate for IVC (7270 Pa/min) was slower than that for VC (9090 Pa/min). The drying of the casing [shown in Figure 3D] along with formation of a lipid layer toward the end of VC resulted in a longer cooling time of VC (Feng and others 2012c). As depicted in Figure 3, the visual appearance of VC-cooled sausage was much rougher and the color was darker than that of IVC ones. However, the surface improved after 4 d of cold room (4 °C) storage, probably because of the elastic and hygroscopic nature of the natural casing (Feng and others 2012c). Qiao and others (2012) also reported on the quality attributes of emulsified sausage (0.1 kg) after being cooled by VC and immersion cooling–vacuum cooling (IC–VC). The sausages were finally cooled to 20 °C. According to sensory analysis results, vacuum-cooled sausage received a lower score because of its uneven surface and poor mouthfeel and chewing quality (Qiao and others 2012). The authors attributed this observation to the violent water evaporation and the different pressures between interior and exterior of the casing, leading to the casing pressed and adhered to the void space of sausage filling (Qiao and others 2012).

As the ultimate temperature of vacuum-cooled sausage can only achieve 10.4 °C (Feng and others 2012c), it is more reasonable to cool sausage using IVC if a lower final temperature (4 °C) is required. In order to enhance the cooling rate of IVC without compromising the quality of the sausage, different levels of water applied in IVC of sausage were also studied (Feng and others 2012d). The distances between water and sausage surface were 16.5 cm for high water level (HWL), 10.9 cm for middle water level (MWL), and 6.1 cm for low water level (LWL), respectively. The final temperature for sausage at LWL was reported to be able to reach below 4 °C, as compared with 8 °C for HWL and 6 °C for MWL (Feng and others 2012d). The cooling times to 10 °C for HWL, MWL, and LWL were 34.5, 25.0, and 21.4 min, respectively (Feng and others 2012d). The reduced evaporation as well as the poor heat exchange toward the end of the IVC procedure may explain this phenomenon. Further investigation demonstrated that the water temperature for HWL at bottom, middle, and surface positions were dissimilar: 9.4 °C at the bottom, 6.3 °C in the middle, and 3.9 °C at the surface (Feng and others 2012d). If no

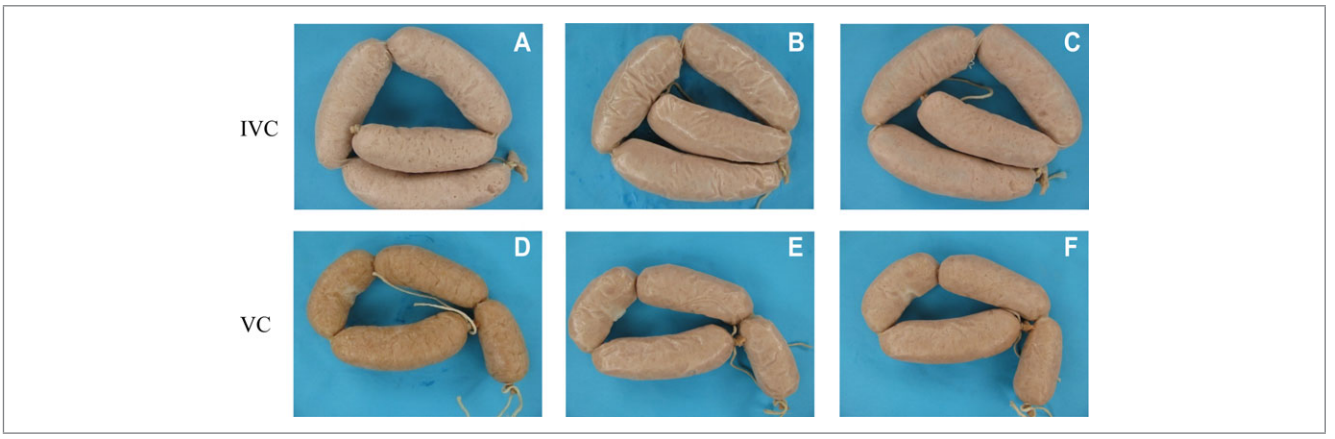

Figure 3–Natural-casing sausage cooled by IVC and VC (Feng and others 2012c). (A) and (D) Immediately after cooling; (B) and (E) after 4 d of cold room storage (4 °C), vacuum pack; (C) and (F) after 3 h exposure (25 °C) of the same 4 d of cold room storage (4 °C), vacuum package sample.

agitation promotes the heat exchange between sample and surrounding water, as well as water at the bottom and the surface, the achieved final temperature will be negatively affected and the cooling time will be greatly extended.

IVC of 2 different types of sausages, with natural casing and artificial casing, was explored by Feng and others (2014a). Results revealed that it was feasible to apply IVC to these sausages stuffed in different type casings as long as the applied pressure drop rate did not exceed the limit pressure resistance of each type of casing (Feng and others 2014a). To be specific, the maximum pressure drop rates during IVC were 10000 Pa/min for natural casing sausage and 3000 Pa/min for artificial casing (Feng and others 2014a). The cooling time (to 4 °C) for sausage made from natural casing was considerably shortened after applying the agitation, whereas no statistically significant ($P > 0.05$) differences were found in cooling times to 4 °C for sausage made from artificial casing (Feng and others 2014a). This may be due to the high hydrophilic ability of artificial casing material, but most likely can be attributed to the lower pressure drop rates applied for the sausage in artificial casing (Feng and others 2014a). Quality of sausages varied depending on the used casing: artificial casing sausage under linear pressure drop rate of 3000 Pa/min without agitation (L 3000) showed significantly lower texture property values than that with agitation (LA 3000) ($P < 0.05$); while natural casing sausage under linear pressure drop rate of 6000 Pa/min with agitation (LA 6000) presented lower texture attribute values than that without agitation (L 6000) ($P < 0.05$) (Feng and others 2014a).

As discussed above, both natural and artificial sausages were able to be cooled using IVC if the proper pressure reduction rates were chosen. However, the IWT and condensing temperature, which are important operational parameters during IVC processing, were not considered in that case. Consequently, Feng and Sun (2014) assessed the combined effects of 4 factors (IWT, pressure drop rate, agitation speed, and condensing temperature) on cooling and quality properties of IVC sausage using response surface methodology (RSM). Polynomial models were developed to establish the relationship between the 4 operational parameters and quality attributes, and finally to optimize the operational conditions for being in compliance with product safety requirements. Results showed that the polynomial regression models derived for cooling time and hardness were different at a 5% significance level. It was figured out that condensing temperature significantly influenced cooling time ($P < 0.001$) (Feng and Sun 2014). This is consistent with the previous statement that condensing temperature will affect the VC efficiency of meat products (Wang and Sun 2004). Significant interactive effects (pressure reduction rate × condensing temperature and agitation speed × condensing temperature) on cooling time were observed ($P < 0.05$). It was also pointed out that the interactive effect was greater when a higher condensing temperature was employed (Feng and Sun 2014). The interactive effects caused by IWT and pressure drop rate positively influenced hardness ($P < 0.05$). The authors attributed these findings to the melted fat and extensive moisture loss when a high pressure drop rate with a high IWT was applied. The decreased fat content in the meat core led to an increased hardness value (Feng and Sun 2014). Consequently, the most feasible and practical operational combination setting for IVC of sausages were suggested as follows: 4.5 °C for IWT, 7290 Pa/min for pressure reduction rate, 459.1 rpm for agitation speed, and −8 °C for condensing temperature (Feng and Sun 2014).

The main reason to maintain a comparably lower pressure drop rate during IVC of sausage is to reduce the burst incidence of sausage. Another alternative method to increase the success rate of sausage during IVC is to modify the natural hog casings' mechanical properties. Combination of surfactant solution and lactic acid was employed to modify the natural hog casing (Feng and others 2014b). Polynomial regression models on mechanical properties of cooked/uncooked treated casings were established. The results showed that the burst pressure and maximum rupture force of uncooked treated casing were negatively and linearly affected by soy lecithin concentration ($P < 0.05$) (Feng and others 2014b). For cooked treated casing, a lower concentration of soy lecithin with a higher level of soy oil resulted in higher burst pressure resistance. For both cooked and uncooked treated casing, an increase in soy lecithin concentration weakened the pressure resistance of the casing (Feng and others 2014b). This may probably be due to the formation of a waterproof layer which, consequently, decreased its water vapor permeability and built up the internal pressure. For validation, sausages were prepared using modified casing with best resistance of burst pressure or rupture force. There was no incidence of bursting for sausage stuffed in modified casing, demonstrating that treated casings were able to withstand the higher pressure difference imposed by IVC (Feng and others 2014b). Further investigation examined by light microscopy and transmission electron microscopy discovered that casing became

more porous after modification, which may be responsible for the low incidence of burst during IVC (Feng and others 2014b).

Microbial risks of products cooled by IVC

From a food safety point of view, meat cuts should be protected from microbial contamination in spite of how meat products are prepared or cooked. Temperature is absolutely a major factor affecting the microbial spoilage (Cayré and others 2003, 2005; Li and others 2013). A cooling method with a long cooling time can enable a pathogen that survived cooking to have enough time to recover and to multiply under conditions that favor its germination (Juneja and others 2008, 2009, 2010a, b, 2011). As a result, different cooling methods with different cooling rates may influence bacterial growth in foodstuffs.

The microbial behaviors in inoculated beef joints (1.0 kg) during different cooling methods, namely VC, IVC, and air blast (AB) cooling, were studied by Drummond and others (2009). Microbial analysis was preformed immediately after cooling and cooking. Results showed that the total aerobic counts of IVC samples without inoculation were not detected at day 0, compared with 3 log unit increase in VC and AB cooled samples (Drummond and others 2009). For inoculated samples, the count of *Geobacillus stearothermophilus* in IVC samples was slightly lower than that of AB samples but higher than that of VC samples (Drummond and others 2009).

Du and others (2014) reported that the microbial counts of sauced chicken cooled by VC and IVC were considerably lower than those of AB and natural cooled (NC) samples during 18 d of cold room storage (4 °C). Total viable counts (TVCs) for samples with NC treatment reached 6 log CFU/g after 10 d storage, compared with 15 d for AB and 18 d for IVC and VC samples, respectively (Du and others 2014). Conclusions can be drawn that microorganisms in meat were inhibited after IVC or VC procedure and consequently minimized the risk of microbial growth in the cooked meat.

The TVC of plain chopped pig's trotter during IVC–VC was investigated by Chen (2014). The detected TVC counts were 1.6 log CFU/g for VC samples, 1.9 log CFU/g for IVC samples, approximately 2.2 to 2.4 log CFU/g for IVC–VC samples, and 3.0 log CFU/g for water immersion-cooled samples. The comparably higher TVC counts in the IVC–VC group may be due to the drainage of surrounding water after IVC procedures, which may have introduced bacteria during handling (Chen 2014). A lower intermediate temperature (25 °C) used in the IVC–VC group obtained a lower count (2.2 log CFU/g) than that with a higher intermediate temperature (35 °C; 2.4 log CFU/g), although no significant differences were seen ($P > 0.05$) (Chen, 2014).

Since the sausage filling is composed of ground or chopped meat, the surface microorganisms are distributed throughout the entire sausage matrix (Mendonca 2010). The preservation methods of sausage, which includes chemical reagents or physical and packaging methods, have been extensively studied during the past decade (Roller and others 2002; Diez and others 2009; Siripatrawan and Noipha, 2011; O'Flynn and others 2014). However, cooling is also an effective method for prolonging the shelf-life of perishable food products. The microbial behaviors in sausage cooled by different cooling methods after long-term storage (4 °C, 29 d) were investigated by Feng and others (2013b). IVC with cold water (20 °C) (IVCC) retarded microbial appearance in sausage during 29 d of storage and showed better quality in accordance with color evaluation (Feng and others 2013b). It was also discovered that lactic acid bacteria (LAB) counts were much higher than *Enterobateria* or *Pseudomonas* counts (Feng and others 2013b) during storage, indicating that LAB were the main bacteria that affected the sausages' shelf-life. Accordingly, IVCC, which can better ensure shelf-life stability, was chosen as a representation for the study of LAB and TVC during a 71-d storage (Feng and others 2014c). The growth rate and lag time for different cooling methods were calculated. Compared to the time-consuming and expensive traditional microbial enumeration methods, predictive mathematical models are cost-saving resources and provide a matrix of microbial growth responses to a broad range of cooling methods. The predicted lag times for LAB and TVC in IVCC were 12 and 9.4 d, respectively. The predicted shelf-lives for IVCC and commercial cooling (immersion cooling) were reported to be 27 and 24 d, respectively (Feng and others 2014c). Different initial microbial counts in the raw sausage filling would influence the later storage, despite post-heat handling and cooling processing (Feng and others 2014c). The comparable higher initial microbial counts mean better opportunity for bacteria left after the processes, thus posing a high risk during long-term storage. Qiao and others (2012) showed the shelf-life for sausages cooled by immersion cooling (IC) or AB (22 d) were shorter than that cooled by VC or IC–VC (25 to 27 d), which may again be due to the comparably lower cooling rates of IC and AB. Juneja and others (2010b) demonstrated that a rapid cooling method was recognized as another efficient approach to delay bacterial growth in cooked ground pork.

Recent mathematical modeling of IVC

The mathematical model developed by Drummond and Sun (2008b) has successfully predicted the cooling losses and described temperature changes in the surrounding water and beef surface and core. The measured mass losses were approximately 2% higher than the calculated mass loss for surrounding water and 1% lower than the calculated mass loss for beef joint. The underestimated calculated mass loss for surrounding water may be due to the extensive water spillage during IVC processing. The overestimated predicted mass loss for beef joint may be caused by water infiltration into meat pores when the vacuum breaks. The predicted water and beef temperatures were in good agreement with experimentally measured temperatures, with a maximum deviation of 7 °C for surrounding water and a 5 °C temperature deviation range for meat surface. As IVC is incorporated with water evaporation, thermal conduction, and convection, the model was mentioned to be more adequate to describe the heat and mass transfers during the phase when the water evaporates in the IVC processing (Drummond and Sun 2008b).

The effects of beef size, porosity, and pressure reduction rates on IVC were continuously studied using finite difference (FD) methods (Drummond and Sun 2012). A larger meat product (radius: 6.5 cm, weight approximately: 2.5 kg) was recommended for a higher pressure rate during IVC (Drummond and Sun 2012), in order to comply the rigid safety requirements (USDA 1999). According to the mathematical model developed by Drummond and Sun (2008b), an inverse relationship between the sample size and calculated mass loss was observed. Porosity, which is not only the intrinsic property of the products but also is generated during the preparation step, positively affected the cooling rate as expected. However, an increase of porosity increased mass loss of the products. For example, the calculated cooling time to 10 °C can be reduced from 160 to 60 min if the porosity is increased from 2% to 5%. However, the calculated mass loss increased from 4% (porosity: 2%) to 7% (porosity: 5%) (Drummond and Sun 2012). An increase in product size could compensate for the large mass

loss with an increase of porosity. According to the simulated cooling time of samples with different sizes under different pressure reduction rates, the effect of increasing pressure reduction rate was gradually lowered with an increase of sample sizes (Drummond and Sun 2012).

The growths of LAB and TVC in the IVC-cooled samples were fitted using Baranyi models (Feng and others 2014c). The growth of LAB in IVCC was better described by fitting the Baranyi complete model (with lag) with a higher R^2 (98.3%) and a lower RMSE value (0.3). The predicted growth rate of LAB (0.7 ± 2.9 log CFU/g/d) was more rapid than TVC (0.5 ± 0.1 log CFU/g/d) in IVCC samples, which was due to the inhibitions of each strain and therefore lowered the mean value of the TVC.

Some Suggestions on Improvement of IVC and Future Trends

Although IVC can achieve a comparably higher cooling rate than conventional cooling methods without sacrificing the quality attributes, it still faces some inherent limitations in terms of its application, rapid cooling rate, food safety concerns, and initial investment. Because of its evaporative cooling principle, the application field of IVC is mainly restricted to the porous food items. If packaged, the packaging materials should be permeable or perforated. Unlike VC that can be widely applied to vegetables, fruits, bakery products, and horticultural products, the foodstuffs that are ideal for IVC may be limited to products that can be immersed in the water such as cooked meat or ready-to-eat meal. Although some efforts, such as using different IWTs, employment of agitation, and combination of IVC with other cooling methods, are made to enhance cooling rate of IVC for cooling products from 72 to 4 °C, the cooling rate of IVC is still slow compared to that of VC. For example, it took only 50 min for VC of pork (1.5 ± 0.1 kg) from core temperature of 72 to 10 °C, compared with approximately 80 min for VC–IVC and 150 min for IVC (Dong and others 2012). It is noticeable to deduce that the cooling time will be greatly extended if the final core temperature needs to achieve under 4 °C.

As IVC introduces water to VC processing, there is a food safety concern for potential cross-contamination (if the water is not sanitary). A study of the effects of VC of lettuce inoculated by *Escherichia coli* O157: H7 was carried out by Li and others (2008). Vacuum-cooled heads of lettuce showed 2 log more of cell recovery than control groups. The authors attributed this observation to enlarged stomata in the tissue in vacuum condition. Likewise, for IVC procedure, there was concern on whether the internal structure of the products would be changed (to be porous) after IVC procedure and thus become easier for bacteria to invade. More studies deserve to be done to confirm this assumption.

For small-scale manufacturers, the initial investment necessary of IVC equipment may be too high to afford. Measures, such as installation of small-capacity vacuum pumps or leased equipment, need to be taken to cut the cost of using IVC.

In order to be conducive to accelerating the cooling rate of IVC, while maintaining the nutrition and acceptable mouthfeel quality provided by IVC, the parameters most likely to affect and control the IVC procedures are likely to be the subjects of continuous investigations.

Agitation was suggested several times to improve cooling rate of IVC via enhancing the conductive and convective heat transfer (Drummond and Sun 2008b; Cheng and Sun 2006b; Feng and others 2012a). It indeed improved heat transfer after the main evaporative stage of cooling (47.4% cooling time reduction after employing agitation) (Feng and others 2013a). However, the cooling time from 10 to 4.6 °C still occupied one-third of the entire total cooling period (Feng and others 2013a). It was pointed out that agitation did not thoroughly homogenize the surrounding liquid from the top and bottom layers. As a result, the top layer had a lower temperature and tended to form an ice layer, especially at the later stage of IVC. This ice layer will act as a lid to prevent further water evaporation and heat exchange, thus resulting in a longer cooling time. A stronger agitation or an agitation applied to different water positions was suggested in order to include the top and bottom layers of the liquid.

It was mentioned that a 3-cm-thick ice layer formed at the end of the IVC processing (Feng and others 2013a). This is undesirable as samples need to be removed at the end of cooling. To prevent thick ice formation while keeping the surrounding water at a low temperature, a new final pressure control method needs to be applied. For example, the surrounding water temperature was maintained at 2 °C by regulating the chamber pressure. When the water temperature is over 2 °C, the chamber pressure is decreased until water temperature gets to 2 °C and then is kept at this value. Likewise, the chamber pressure will be gently increased when the water temperature is monitored below 2 °C.

Although many research studies have been done in relation to the effects of IVC of meat products on quality and cooling attributes, the knowledge gap of optimizing IVC operations on foodstuff, like sausage stuffed in artificial casing, needs to be filled. Furthermore, the effects of IVC of meat products on nutritional attributes must be investigated in future work.

Conclusions

This review addresses the progress made in recent years in developments on IVC technology for the meat industry. Different types of large and small meat products have been extensively studied. For large meat products, the water used in IVC should be kept at a minimum. IVC-cooled samples became more tender and showed a weaker redness than VC-cooled samples. There were no considerable differences between samples cooled by IVC with different IWTs in terms of moisture and protein contents, WHC, and WBs. IVC of 2 pieces of hams together did not show substantial differences in relation to textural properties and cooling parameters when compared to cooling a single piece. Immersion vacuum-cooling of plain chopped pig's trotter showed satisfactory results when using IVC at 30 °C and then VC. For small foodstuff items, the condensing temperature is known to readily influence the cooling time of IVC. A lower cooling loss and tender chicken breast was obtained using ICK followed by IVC processing. The oxidation of IVC-cooled sauced chicken was greater than natural-cooled one. IVC-cooled sausages can achieve a final temperature of 4.3 °C, whereas 10.4 °C for VC-cooled ones. The differences of texture profiles and color for IVC of sausages using different water levels were insignificant at a 5% significance level. Sausages stuffed in artificial casing obtained lower textural attributes with L 3000, whereas natural casing sausage with L 6000 displayed higher textural properties. For both large and small meat product items, a large amount of vapor generated in the vacuum chamber should be avoided, by addressing proper employment of pressure drop rate, condensing temperature, and IWT. IVC was able to retard microbial growth in samples and so prolong the shelf-life of the meat products. More research is needed to elucidate IVC effects on nutrition and pathogenic microorganisms.

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