Overview of available methods for thawing seafood / Lausnir sem standa til boða við uppþíðingu á sjávarfangi

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Report summary

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Title / Titill	**Overview of available methods for thawing seafood /** *Lausnir sem standa til boða við uppþíðingu á sjávarfangi*		
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Summary in English:	There is a constant demand for quality raw materials that can be used for producing seafood products for high paying markets in Europe and elsewhere in the world. Suppliers of demersal fish species in the North Atlantic are now meeting this demand by freezing the mainstay of their catches, in order to be able to have available supplies all year around. This is partly done because of seasonal fluctuations in catches, which are harmful from a marking point of view. The fact that all these raw materials are now frozen demands that methods used for freezing and thawing can guarantee that quality of the raw material is maintained. There are a number of methods available to thaw fish. The most common ones involve delivering heat to the product through the surface, as with conduction or convection. These methods include water and air-based systems. More novel methods are constantly on the rise, all with the aim of making the process of thawing quicker and capable of delivering better products to the consumer. These procedures are however, often costly and involve specialized workforce to control the process. All in all, it depends greatly on what kind of conditions a company is operating under regarding which thawing methods should be chosen. This report identifies the most common methods available and provides information on their main pros and cons.		
English keywords:	*Thawing, water, air, microwaves, vacuum, fish blocks, seafood, heat transfer, drip, cost, quality*		
Ágrip á íslensku:	Stöðug eftirspurn er frá fiskvinnslum víða um heim eftir góðu hráefni úr Norður Atlantshafi til framleiðslu á afurðum fyrir kröfuharða markaði. Til að mæta þessari eftirspurn og með hliðsjón af miklum árstíðabundnum sveiflum í veiðum á vissum fisktegundum hafa fyrirtæki gripið til þeirra ráða að frysta hráefnið til notkunar síðar meir. Það kallar á góðar aðferðir til að frysta hráefnið, en ekki er síður mikilvægt að þíðing hráefnisins sé góð. Til eru margar aðferðir til að þíða fisk og aðrar sjávarafurðir. Algengast hefur verið að nota varmaflutning í gegnum yfirborð með varmaburði eða varmaleiðni. Þær aðferðir byggja að mestu á því að nota vatn eða loft sem miðil til þíðingar. Nýrri aðferðir eru til sem reyna að gera ferlið fljótvirkara og þannig skila betri afurð til neytenda. Þessar aðferðir eru þó oft kostnaðarmiklar og fela í sér mikla sérhæfingu starfsfólks. Þegar öllu er á botninn hvolft, skiptir máli um hverslags rekstur er að ræða og hvernig aðstæður fyrirtæki búa við hverju sinni þegar þíðingaraðferðir og tæknilegar lausnir eru valdar. Í þessari skýrslu eru tilgreindar allar helstu þíðingaaðferðir og þær tæknilegu lausnir sem eru á markaðinum í dag, ásamt því sem helstu kostir og gallar þeirra verða tilteknir.		
Lykilorð á íslensku:	*Þíðing, vatn, loft, örbylgjur, lofttæmi, fiskblokkir, sjávarafurðir, varmaflutningur, drip, kostnaður, gæði*		

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Introduction

European markets depend to a large extent on a constant supply of raw materials for food processing and the fishing industry is no exception. The demand for high quality raw materials is growing constantly and it is getting increasingly difficult to meet that demand. Norway is a leading supplier of North Atlantic cod and the mainstay of their catches are concentrated on the first few months of the year, mainly through late January to middle of April when the Barents Sea cod gathers along the North-Norwegian coast to spawn. About 2/3rd of the Norwegian cod catches are caught during this three-month period (Fiskeridirektoratet, 2017). This seasonal spike in supply calls for methods of storing the raw materials for later processing to distribute the load throughout the year and to be able to supply the market with high quality products all year round. In order to store the fish for later processing, it has to be frozen and kept at constant temperatures as low as -25°C to -50°C. When processing of the material is due, the frozen product must be thawed in order to convert the raw materials into final products. The process of thawing is an important parameter in determining the final quality of the products being produced; with many different thawing methods existing. This report aims to provide a found basis for thawing by gathering information from various documents and reports and out-listing the pros and cons of each thawing method. New ways of dealing with the thawing of frozen fish will also be touched upon, although the most common methods will be the centre of discussion.

The process of thawing

Thawing of food products is essentially the conversion of frozen water into liquid. The phase change involving the conversion of ice to water requires a lot of energy and usually happens at a gliding temperature in foods. Due to the fact that a large amount of energy is needed to complete this phase change, products being thawed often experience extended amounts of time in this gliding temperature zone as seen on figure 1 (Haugland, 2002).

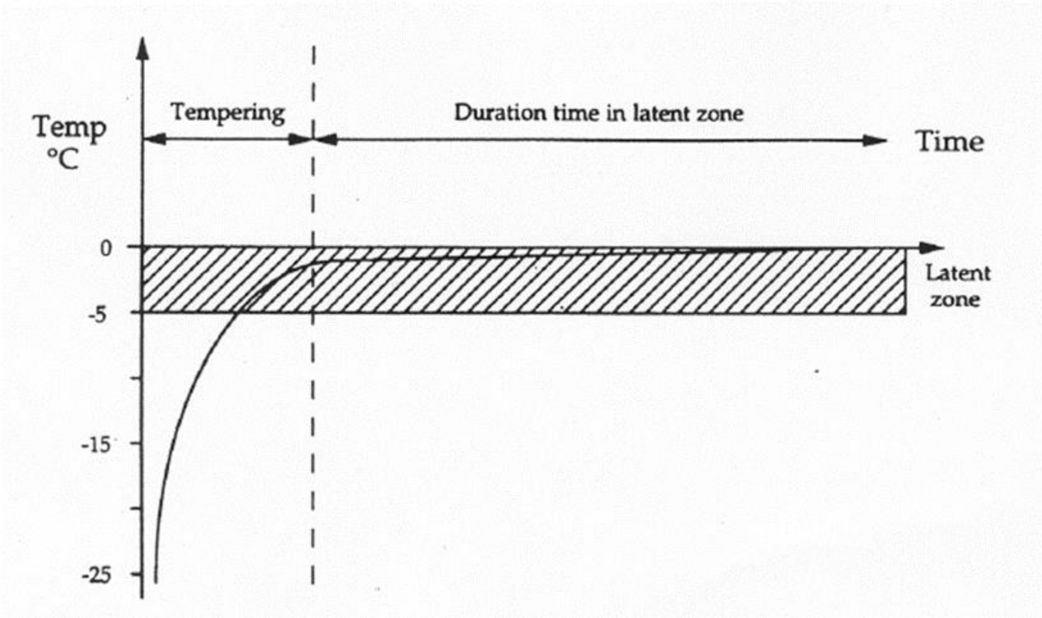

Figure 1: Gliding temperature range of food thawing

Thawing is the exact opposite of freezing, where freezing removes heat from a product and thawing provides heat to the product. However, thawing is a much more delicate process and more difficult to handle in relation to thawing food products and great care should be taken if the material quality is to be kept as good as possible. This is especially relevant for the fish industry, as fish meat is usually more susceptible to outer factors regarding deterioration and damage of the raw material than other meat products.

There are several reasons why thawing is more difficult than freezing. First of all, the thermal resistance of the product increases as the thawing process progresses. This is opposite to what happens in freezing, where the outer most layers of the product begin to freeze and generate a conduction surface for the heat to escape through. Secondly, thawing cannot be carried out at any temperature. That is, the difference between the initial frozen product temperature and the thawing medium temperature can only be at a certain interval in order not to damage the products. This is especially important in processes where heat is applied to the product through the surface.

Fish as a material is a very difficult problem to deal with in terms of thawing. The relative water-fat-solid compound ratios in the fish muscles differ in between species, the time of year and what the fish has been eating. Lean fish is mostly water, up to 82% in some cases. This means that it is easier to freeze and thaw lean fish than fish with more fat content, as fish with more fat content has a lower percentage of its weight in the form of water. As mentioned previously, the phase change of frozen water into liquid during the thawing process takes place at a gliding temperature in food products, as per figure 1. The slope of the temperature curve is dependent upon the thawing medium temperature as well as the relative water-fat-solid ratios in the fish muscle. Often, the fish muscle experiences extended periods of time in this zone. This time is critical and has been shown to increase loss of water content through drip considerably (Haugland, 2002). Longer thawing times also encourage the growth of bacteria in the outer most layers of the fish, with the surface reaching temperature as high as the surrounding medium while the core is still in the thawing process. It is therefore important that the thawing is carried out in a controlled manner and as quickly as possible in order to retain the quality of the thawed material. It has been suggested that thawing has a positive effect on bacterial decline in a fish muscle although it has not been proven (Archer, Edmonds, & George, 2008). One possible explanation is that during thawing, ice melts which overflows the muscle with water and small bacteria experiences a so called osmotic shock. This can however also have negative effects on the fish muscle itself and therefore repeated freezing and thawing cycles are not recommended as means to lower the numbers of bacteria in the product.

The thawing process can take place by two different types of concepts. These concepts differ in terms of how the heat is supplied into the fish muscle. The first and the most used one is by supplying heat through the surface. This can be done by convection, conduction and radiation. The other is by generating heat within the product, thus making the thawing a more uniform process. The latter methods, though seemingly beneficial for the overall product quality, often are not possible to implement in terms of complexity and the scale of the production. These methods include microwaving, ultrasound and electrical resistance.

What method a company decides to use for its thawing purposes relies on several factors including cost, throughput, efficiency and effect on the quality of the fish. Companies dealing with large batch sizes rely mostly on water or air related thawing, but smaller scale industries such as restaurants are capable of using microwave thawing. It is clear that the size of the samples also impacts the choice of methods, but sample sizes can vary from small fillets up to whole blocks of frozen fish, often around 50 kg.

Thawing methods

As touched upon in previous chapters, there are two main concepts regarding how the thawing of fish products is carried out. This can either be done by heat transfer through the surface of the fish or by heat generation within the product. Both methods differ in terms of cost, possible batch sizes, available temperature regions and more. Therefore, a company has to choose which concept to implement and what method to use prior to setting up a facility intended for thawing. That depends upon the respective company status and which type of industry it thrives in.

Conventional methods - Heat transfer through surface

Methods that involve heat transfer through the surface of the product being thawed are still to this day the most used methods. The reason for that is mainly that they are relatively inexpensive to implement and can be convenient for companies thawing large quantities or batches at a time. The heat transfer through the surface can happen through:

- Convection/Conduction
- Condensation (usually water in the form of vapour)
- Radiation

The most common way is introducing processes which involve convection and conduction, though all types of surface heat transfer could be used in parallel. These methods are, amongst others, immersion in water and air-blasting. What the surface methods all have in common is that the thawing rate is not constant and it slows down as time goes on. This is due to the fact that the outer layers thaw first, increasing the thermal resistance of the product, isolating the core that is still frozen. This can be dangerous if the thawing medium temperature is too high, resulting in overheating of the surface and thus damage of proteins and increased bacterial growth. It has therefore been advised that the temperature of the thawing medium should not be higher than 5-10°C (Archer, Edmonds, & George, 2008). The product should then be sent to storage at temperatures close to the respective initial freezing point before processing. Results show that for the thawing of salmon, the most efficient way of achieving the best possible raw material is to immerse the frozen salmon in water at 5-10°C and then chill towards the desired temperature (Haugland, 2002).

Different types of thawing respective to heat transfer through the surface of the product will now be tackled further.

Still air thawing

Thawing in still air is a widely-used method largely due to the fact how easy it is to implement. However, the quality of the raw material acquired after still air thawing depends largely on how the process is carried out and the respective ambient temperature. As the fish blocks/fillets are laid out to thaw, they create a boundary layer around them, resulting in cooler air temperatures close to the surface of the thawing product. This slows the heat transfer from the product to the environment down considerably and therefore the overall thawing will take longer. One of the most likely reasons for why this method is still used is that there is little to no cost involved by thawing in still air. In many cases, the fish blocks/fillets are laid onto the factory floor to thaw overnight, or placed on specific racks, as seen on figure 2 (Archer, Edmonds, & George, 2008).

Figure 2: Thawing in still air. Fish is placed on special racks that stand on the factory floor

This, however, is usually done in an uncontrolled environment which results in worse quality of the final product. The thawing is often carried out at room temperature, while in some cases the fish might be left to thaw in a freezer at 0-4°C. This slows the thawing process down and for large blocks of fish the thawing in these circumstances can take up to 20 hours. This time can be improved for blocks of fish by separating the single pieces from the block as soon as possible. As soon as the fish is no longer in blocks, the thawing time can be accelerated down to 8-10 hours (Archer, Edmonds, & George, 2008).

- **Effects on drip loss**

  When thawing in still air at constant temperatures, the fish/blocks create a boundary layer around them as was described earlier. This slows the thawing down so that a large part of the fish muscle experiences extended amounts of time in the gliding temperature zone shown on figure 1. The amount of drip released by the muscle during this thawing process is, though dependent upon the total thawing time, also determined to some extent by how the product was frozen. Rapid freezing has been shown to produce less drip as the ice crystals that form in the muscle are smaller and therefore won't be released as large drops of accumulated water during thawing. Some reabsorption of water has been reported during thawing and therefore rapid thawing has been shown to induce more drip loss in fish products if they were not properly frozen, but with most fish products today, rapid freezing techniques are applied. Therefore, slower thawing is not recommended (Archer, Edmonds, & George, 2008).

- **Effects on fish muscle and bacterial growth**

  The impact still air thawing has on the muscle relies to some extent on total thawing time and pre-freezing conditions of the fish. Slow thawing can result in dehydration of the fish muscle with the outer layers becoming dry while the core is still experiencing thawing. This will accelerate bacterial growth where the muscle has already been thawed, especially when the ambient air temperatures are in the region of 15°C or warmer. The proteins contained in the fish muscle can also transform when exposed to high temperatures, causing irreversible effects in the fish muscle. This will not necessarily damage the muscle but the quality of the final product will be dramatically reduced.

  When blocks of fish are placed on a factory floor to thaw overnight, chances are that foreign bacteria can damage the products along with microorganisms already in place, accelerating the decline of the muscle even further. These practices are still used in some places of the world, despite their clear negative impact on the product quality.

- **Batch sizes and space requirement**

  Due to the fact that ambient air thawing takes relatively long periods of time, especially if the temperature is low, large batch sizes are not recommended for best quality of the thawed product. Furthermore, the product size should also be as small as possible. Large fish blocks are therefore not ideal for thawing at room temperature in still air.

However, due to the process being easy to implement, the thawing of fillets for immediate consumption in home kitchens and restaurants could be a possible solution even though most respectful commercial kitchens use other methods for thawing their frozen fish products.

This method requires considerable space as well, as the products being thawed cannot overlap, so large batch sizes have to be distributed over a wide area for a long time. This is a reason for why it can be beneficial for companies short of space to resort to other types of thawing, for example water immersion or air blasting.

- **Costs**

  It has already been mentioned that the cost of still air thawing is low and it is therefore still practiced where firms cannot afford machines to accelerate and improve the process. Often the products are laid on the floor to thaw with no lights or heat circulating the room, so that the only cost is the renting/usage of space. Some companies however, heat their rooms up to a desired temperature or cool them down to 0-4°C. This requires that some of the work needs to be done by a heat exchanger, but still should not be too financially inflictive.

- **Pros and cons of still air thawing**

  As listed above, there are few ways that still air thawing could be justified, but the overall cons of this method outweigh the pros by some margin, especially when handling large batch sizes, which is not at all recommended.

  The pros mainly include:

    - Lower cost.
    - Little or no maintenance of tools/machines.
    - Not overly spacious for small quantities.

  The cons, on the other hand are:

    - Material quality is compromised.
    - High drip loss.
    - Slow thawing compared to other methods.

- Parts of product can overheat in ambient temperatures.
- Accelerated bacterial growth due to slower thawing.
- Spacious method for large quantities, thus only justifiable for small batches and fillets.
- Can be very unhygienic if care is not taken.
- Ambient temperature fluctuations throughout the year.

Forced air/blast thawing

Opposite to still air thawing, forced air/blast thawing involves stimulating the air around the products to be thawed. The air is then circulated so that the boundary layer formed in still air thawing does not form and isolate the frozen product from the warmer air. By doing this, the convection coefficient can be increased from around 15-30 up to over 100 $\frac{W}{m^2K}$ so the overall efficiency of the process is increased. Usually these methods involve some kind of enclosed rooms specially equipped to thaw fish blocks in specific batch sizes. Therefore, these rooms are built in similar fashion as those designed to dry fish. The most sophisticated designs involve air fans capable of alternating flow directions and a sprinkler system to keep the moisture content of the air at a defined interval. However, the simplest equipment usually just consists of an enclosed room with air circulation. This can though lead to overheating in some areas and calls for rearranging the products to be thawed to get even distribution of thawing rate. A basic forced air thawing room schematic is shown on figure 3 (Archer, Edmonds, & George, 2008).

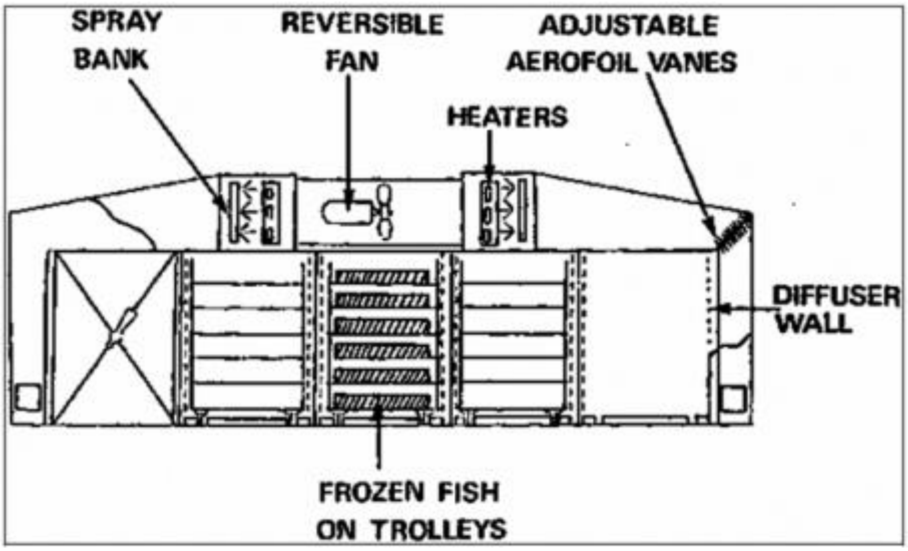

Figure 3: Schematic of a typical forced air/blast thawing room

It is not advised to use higher air temperatures than 20-25°C and for computer controlled thawing rooms, the temperature should be constantly decreased as the products get warmer. By doing that, the drying of the outermost layers of the fish is avoided. Thawing fish up to the initial freezing point and then allowing it to temper is then advised to keep the material quality as high as possible after thawing. The maximum product temperature should never go over 5-7°C during the thawing process to minimize bacterial growth and drying.

- **Effects on drip loss**

  As with the thawing in still air, the force air method can have negative effects on drip, especially since the thawing rate is higher. Like stated in the previous chapter, fish muscle has been shown to have a tendency to reabsorb some of the water that has been lost from the muscle during freezing. However, this reabsorption is dependent upon the thawing rate and since forced air thawing induces higher rates than still air thawing, the danger is that more drip loss is experienced during this process. However, by keeping the humidity of the air sufficiently high, drip loss can be minimized. This is only available as a solution in rooms equipped with water spray systems, or similar methods.

  In order not to overheat or dry the fish closest to the inlet of air, the flow circulation has to be reversed a few times during the thawing process. If alternating the direction of the fan is not possible, then the fish racks must be rearranged during the process.

Another way to minimize the drip is to thaw the fish up to initial freezing point and then apply tempering to even out the temperature of the batch.

- **Effects on fish muscle and bacterial growth**

  There are similar dangers of damaging the muscle proteins as with thawing in still air when using blast rooms. The difference is that the thawing process is quicker and can be more accurately controlled. However, that is still a problem since it is nearly impossible to know the accurate temperature of every fish in each batch. Therefore, the programs usually have a tendency to be too long or short, resulting in over or under thawed products. Usually these rooms also create hotspots on certain locations where warm air gets trapped and overheats the products nearby, often causing irreversible changes in the fish proteins.

  Since the ice to water conversion process is quicker during blast thawing, the bacterial growth most often does not equal that of still air thawing techniques. However, in the cases when specific parts of the blast rooms overheat, the growth of unwanted microorganisms might accelerate. It is therefore vital to place several temperature sensors throughout the thawing rooms to monitor all areas.

- **Batch sizes and space requirements**

  For most of the blast air thawing methods today, the process is not continuous. Large majority is thawed in batches but the sizes of those batches differ depending on the respective company industry. A lot more can be thawed at a time than with still air since the fish is placed on racks inside the chamber and air circulation is ensured.

  For systems applying continuous thawing there is no need to define specific batches. These methods rely on constant supply of frozen blocks to thaw and are usually the most sophisticated ones, involving precise temperature control as well as water spray techniques. However, these systems are more often used for thawing shellfish and higher quality/value products. Naturally they also take up more space than the equipment involving batch thawing, because of the conveyor belts moving the blocks from one place to another until they are thawed.

- **Costs**

  What drives smaller companies into using still air thawing instead of blast/forced air is the start-up cost of the purpose built thawing chambers. It depends on the batch sizes and the setup of these chambers how much this initial cost is, but it will most likely be in similar regions as the cost of the most typical freezing chambers. This can range from $15,000 all the way up to $400,000 (Hafsteinsson, Högnason, & Arason, 2010). The maintenance cost is also a factor, but these machines need replacements/repairs after a specific amount of cycles. The room must be cleaned regularly to get rid of bacteria, minerals and proteins that might have gotten stuck on the racks, floor and walls of the thawing chamber.

- **Pros and cons of forced air/blast thawing**

  Forced air thawing is not without its drawbacks, even though it is a method that is appropriate in many cases. The main advantages of this method are:

  - Quick thawing rate.
  - Good control of temperature and humidity.
  - Can handle various batch sizes and quantities.
  - Hygienic.
  - Range of different systems and versions.

  The disadvantages are that:

  - Initial cost can be very high for sophisticated systems.
  - Danger of surface drying/overheating.
  - Regular maintenance/cleaning is needed.
  - Hard to acquire uniform thawing.
  - Products might need tempering.
  - Energy cost (water, heat exchangers and fans).

Water sprinkling

The water sprinkling technique is not that much different from still air thawing. However, in this case, water is used to spray the frozen blocks/fish as well to accelerate the process. How dedicated companies are to maintaining hygienic environment for the products varies and some just lay the blocks of fish on the floor before leaving them overnight with the water running. This method only works properly for batches and is most of the time specially made by the company in question rather than being a commercial product, like other water-based thawing systems. A typical setup can be seen on figure 4 (Archer, Edmonds, & George, 2008).

Figure 4: Typical setup of a thawing system using water sprinkling

Details on factors such as drip, costs and bacterial growth and other pros and cons won't be covered for this method like with the other methods, as this procedure has very similar attributes as the still air thawing technique. However, the thawing takes place at slightly elevated rates due to the water sprinkling and due to the products being in constant contact with water there is less danger of drying during extended periods of time spent in the process.

Water Immersion Systems

Immersing the frozen products in water is perhaps the most common version of thawing methods used by commercial companies aiming to thaw large quantities and deliver high quality products. However, the way the process is carried out varies from simply being the storage of blocks in a fish tub/tank overnight to highly sophisticated tanks with temperature control and water filtering systems. These different methods will all be tackled at the same time in this subchapter, but during the discussion of pros and cons of these methods, the category will be split up into conventional systems (simple immersion) and purpose designed systems (temperature control, variable batch sizes and continuity) to give a better overview of different choices available to companies.

Simply immersing the blocks of frozen fish in a tank overnight with the water running requires little knowledge and supervision, but that comes at the cost of obvious quality issues. Figure 5 shows a relatively basic water immersion where the blocks are left to thaw in water for a few hours (Archer, Edmonds, & George, 2008).

Figure 5: Simple water immersion in fish tanks

This means that the circulation of water is not ideal and there is also little or no temperature control during the thawing process. Usually there is little care taken whether the blocks get stuck together, but splitting the blocks as soon as possible has been shown to reduce thawing times for cod (Haugland, 2002).

The issue with this implementation of the water immersing method is also the fact that since there is little recirculation of the water and essentially no filtration, bacteria from guts and blood finds it easy to go from one fish to another and contaminate the whole tank. Lower temperatures of the thawing medium would limit the growth in these instances but still there is always the danger of contamination. The more sophisticated methods involve large tanks with filtering systems, like was mentioned before. These systems clean the water before recirculating it back into the tank, thus saving waste and water. 3X Technologies is one company in Iceland which offers thawing as well as filtering equipment for fish industries. It is claimed that the filtering system offered by them can save companies up to 60,000 litres per week. Their thawing units consists of a rotary tank, which moves the blocks along as they thaw. The thawed fish is then collected in a fish tank along with cooling medium (water) and stored. Melbu Systems in Norway offer a similar solution, where blocks of fish are thawed in a large, temperature controlled, stainless steel tank. GE Verk, located in Iceland, offers similar setup as 3X but without the water filtering system. Their solution however, include a step where the blocks are split prior to the thawing process, shortening the total thawing time in the liquid. SeaGain is yet another company that is marketing novel thawing solutions. As with GE Verk, their solution includes splitting of the blocks prior to the thawing. Figure 6 shows the equipment and set-up that Melbu, 3X, GE Verk and SeaGain are offering:

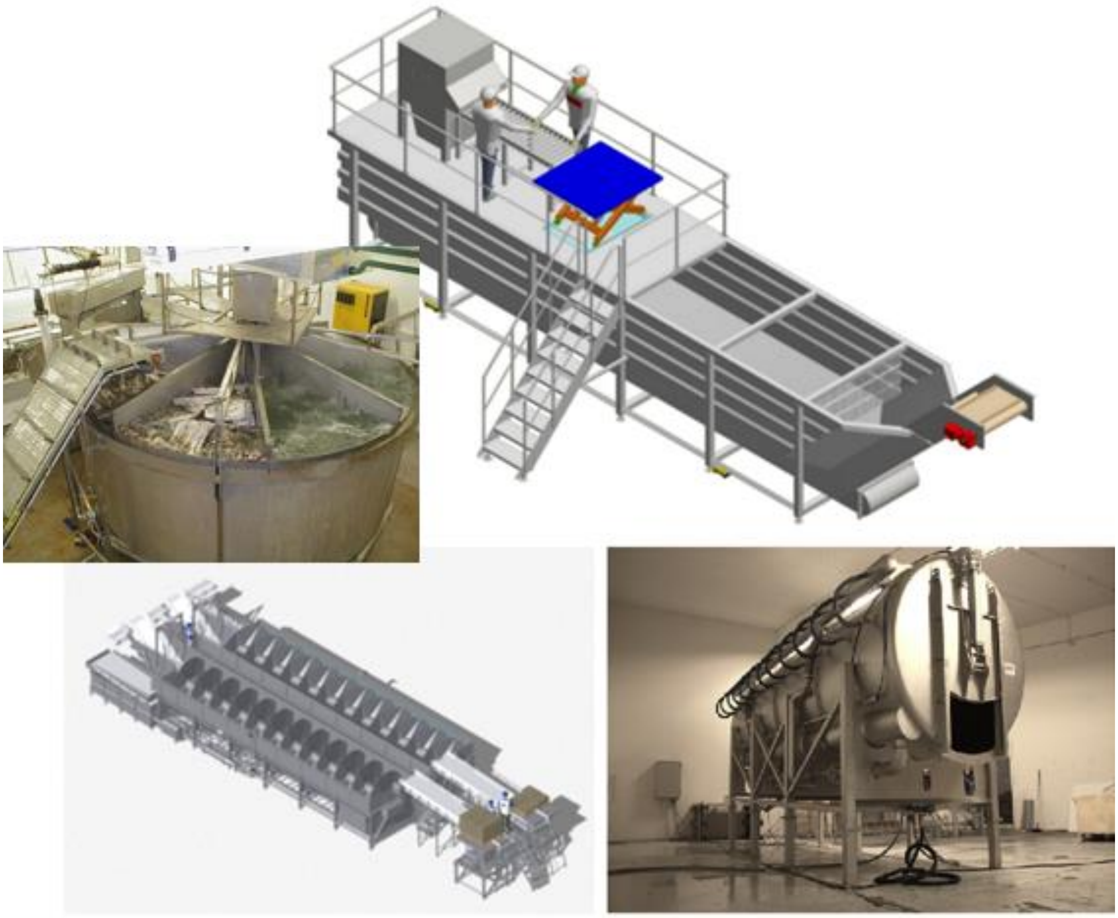

Figure 6: Different types of water immersion thawing equipment from Melbu Systems (top left), SeaGain (top right), 3X Technology (bottom left) and GE Verk (bottom right)

Both 3X and SeaGain apply air injection system which is supposed to bring more circulation to the fluid. The thawing rates with these types of equipment are very high and can reach down to almost 2-3 hours for around 5-6 tons of fish.

- **Effects on drip loss**

  Since the fish is being thawed in liquid, the loss of water through drip is not going to be as much as it normally is with air thawing. However, like touched upon in previous chapters, the drip has been shown to increase with more rapid thawing times as the water is not absorbed back into the fish muscle during thawing. This loss through drip can be as little as 5% of the original product weight but is often much higher for inadequate processes. However, since most freezing is done under controlled circumstances in larger companies producing high quality products, the possibility of high drip loss is not of too much disconcert.

- **Effects on fish muscle and bacterial growth**

  The water immersion methods are numerous and each can have different effect on the final product. The methods involving simply the immersion of blocks in water don not use thermostats and controllers to monitor the temperature of the thawing medium. This can be very problematic as with too cold thawing medium, the process will take too long. Overheating the product can happen as well if the medium is at higher temperatures. Processes with no supervision, i.e. leaving the blocks to thaw overnight, can experience this overheating of the fish and thus reduction in material quality. In fact, reports have stated that yield is increased by having the fish still a little bit frozen in the core, further implying that quick thawing towards -1°C gives the best results for fillet production (Haugland, 2002). This also limits the bacterial growth in the muscles, which can be a problematic issue with water immersion thawing techniques. The thawing medium can act as a highway for microorganisms between fish samples, if the medium is not sufficiently filtered and exchanged. The more advanced solutions therefore all have accurate temperature control of the thawing medium where it is made sure that the product is being thawed at optimal temperature.

- **Batch sizes and space requirement**

  The most modest methods involve batches that are put into water and let thaw. These methods can be from the simplest ones with fish tubs/tanks and garden hoses up to tanks with air infusion systems and temperature control. These systems require less space than their more advanced parallels as they don't involve conveyor belts or any other processes needed for continuous supply of raw material. However, these methods might need more staff to keep them going as the material must be moved into the thawing units and then it has to be moved away from it when the fish has been thawed. The automated systems often offer fully continuous solutions that only require one individual as staff to oversee the process. More space is naturally needed but these systems can get quite compact, especially if they are designed with low material throughput in mind. 3X Technology offer three alternatives each specifying different throughput rates of 2.8, 6 and 10 metric tons.

- **Costs**

  Evidently, as the methods differ extensively regarding complexity and accuracy, the capital and running cost differ as well. For the simplest methods, there is a relatively low capital cost or even none if the company in question already has fish tubs/tanks and storage rooms at its disposal. Then it is just a matter of resources, which could be running water and perhaps some degree of temperature control in the storage. As the design gets more complicated the capital cost gets higher and today there are systems available which implement the simple immersion method but still apply some more sophisticated additional functions. These functions can be air injection into the tanks to improve agitation and separation time of fish blocks, automatic movement of fish tanks when the products have been thawed or temperature control and filtering of the water. It is hard to estimate the initial cost of these methods as the information is not readily available on respective firms' websites and some firms are not ready to give up their pricing unless they find the customer likely to be purchasing their product. However, the Food and Agriculture Organization has put up a reference table where the capital, maintenance, fuel and labour cost are listed in relevance to the cost of air blast thawing. This gives an indication of the total cost of most thawing methods and will be further listed in the summary chapter. On average, they list the capital cost of water-based methods as 80% higher than standard air blast thawing. This is of course not true for all thawing methods with water, as was covered thoroughly earlier. However, the more advanced methods are likely to contribute to higher average value of capital cost due to their nature of complexity. The maintenance cost is then listed similar while fuel and labour cost is ranked slightly lower compared to the air based counterpart.

- **Pros and cons (conventional systems)**

  It should be clear from the discussion during previous points that conventional systems offer simpler executions of the water thawing concepts but lack in other aspects such as hygiene and overall control. The general pros of this methodology can be listed as:

  - Low capital and maintenance cost.
  - Can be modular, i.e. don't require much space.
  - Easier to clean due to their simplicity.

  The cons, on the other hand are:

  - Hard to keep track of thawing rates depending on method.
  - Monitoring is often insufficient.
  - Lack of temperature control resulting in reduced quality.
  - Can be very unhygienic.
  - Extensive product handling usually required.
  - Spoilage by using excessive water (running too long/overnight).
  - Just for batches i.e. unable to have continues flow.

  Of course, these are factors derived on average for most conventional systems. Some systems which are not strictly purpose designed can indeed be very advanced and properly executed but that is not often the case.

- **Pros and cons (purpose built systems)**

  As the purpose-built systems are naturally more complicated they offer more possibilities of monitoring the process and improve the product quality. The main pros of these methods include:

  - Thawing in batches and continuous systems available.
  - Designed especially for each purpose.
  - Different programs to implement/control on each machine.
  - Hygienic – often built with water filtering systems.

- Thawing is more often faster – agitation by air injection.

The cons are however inhibiting for smaller firms perhaps not having the financial capacity to afford the more stylish designs. Those include:

- High capital cost.
- Running cost can be high (electricity, water).
- Few systems available.
- Only appropriate for whole fish/blocks.
- More space needed compared to most conventional systems.

Water Immersion Thawing under Pressure (Pressure Assisted Thawing)

Pressure assisted thawing method began gaining attention in the beginning of the 21st century, but the main thought is to lower the melting point of water down to a minimum of -22°C at 209 MPa, by applying pressure to the frozen products and melting the water that way. This enables for a more uniform thawing to be achieved, releasing the water from the ice crystals inside the fish tissue all at the same time. During this pressure thawing process, the size of the product does not matter for uniform and rapid thawing (Galazka, Ledward, Dickinson, & Langley, 1995). Therefore, pressure assisted thawing adds the third main parameter to the thawing process, as temperature and time were the two largest factors before (Schubring, Meyer, Schlüter, Boguslawski, & Knorr, 2003). However, even though the product size does not matter for the pressure thawing concept, most studies on this matter focus on fillet and small samples thawing. That is likely because the pressure applied is substantial and for large blocks of fish, the equipment needed would be massive and expensive. It has been shown that even though pressure assisted thawing can treat the product more uniformly, it can lead to transformations of proteins in the fish (Mozhaev, Heremans, Frank, Masson, & Balny, 1996). One of the factors also affecting the thawing of pressurized products is the lower melting enthalpy, shown to decrease from about 333 kJ/kg at 1 atmospheric pressure unit down to 241 kJ/kg at 193 MPa (Karino, Hanne, & Makita, 1994).

- **Effects on drip loss**

  Applying pressure to the products being thawed results in improved water holding capacities during the thawing process. For some species, this applies relatively well and significant improvements in drip loss can be observed, as shown in figure 7 (Schubring, Meyer, Schlüter, Boguslawski, & Knorr, 2003).

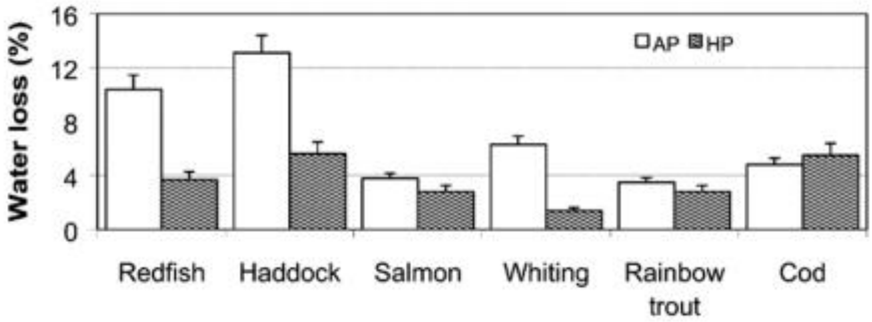

Figure 7: Comparison drip loss when applying high pressure thawing (HP) and conventional thawing (AP) on some common fish species

  The figure shows that there are significant differences in drip loss depending on species. It is though interesting that for cod the difference between pressure thawing and conventional thawing is only marginally better.

  Similar results have been observed in other studies, showing overall decreased drip loss when thawing under pressure (Rouillé, Ramaswamy, & Leclerc, 2002). Most studies suggest 150 MPa to be the most applicable pressure value, as with higher pressures the proteins start to transform more noticeably, which results in decreasing water holding capacities of the fish muscle. Furthermore, positive effects on drip loss have been observed when keeping the product under pressure for longer times after thawing, as it allows water to be reabsorbed into the muscle (Schubring, Meyer, Schlüter, Boguslawski, & Knorr, 2003). The downside is however that for some species that have been thawed under high pressure, increased drip loss has been observed after cooking. This is likely due to the change in myosin fibres and the protein of the fish muscle.

- **Effects on fish muscle and bacterial growth**

  The effects of pressure assisted thawing on the fish muscle itself are likely to be more noticeable that for conventional water or air thawing methods. Like always, the

freezing method is largely determinant on how well the water crystals formed in the fish during freezing, but pressure assisted thawing has nonetheless been shown to have significant impact on denaturation of muscle proteins (Schubring, Meyer, Schlüter, Boguslawski, & Knorr, 2003) (Rouillé, Ramaswamy, & Leclerc, 2002).
Some studies also give an indication of pressure thawing having positive effects on bacterial growth, even extending the shelf-life of salmon by up to two days when exposed to 150 MPa treatment post thawing at 5°C for 10 mins (Schubring, Meyer, Schlüter, Boguslawski, & Knorr, 2003). Colour changes are also expected for high pressure thawed products, with increased lightness and less transparency of fillets. These colour changes then seem to be increased with growing pressure.

- **Batch sizes and space requirement**

  Limited knowledge is available on possible/optimal batch sizes and space requirements for reassure assisted thawing. This is due to the fact that the method has not quite taken off on large scale yet, and perhaps never will. With already available technology there only seems to be a viable option to thaw in batches and the space requirement is similar as for some of the medium size water immersion techniques, all depending on the quantity to be produced. Furthermore, there seem to be mostly fillets that are being thawed using pressure assisted thawing, but not blocks of whole fish.

- **Costs**

  As with the batch sizes and space requirement, there is not much data available on the costs of purchasing, setting up and running solutions applying pressure assisted thawing. However, since this methodology requires the use of water thawing techniques and such operations, the cost should be expected to be at least equal or higher to that of conventional water thawing methods at atmospheric pressure. The pressure being used to thaw the products is quite substantial (150-200 MPa) so the equipment chosen for applying pressures has to be capable of producing those situations, which is quite costly.

- **Pros and cons**

  Reduced thawing times is something that is constantly being sought in companies thawing large amounts of products. However, no method is without its drawbacks and high pressure assisted thawing is no exception. Even though great thawing times can be achieved with less drip loss for some species of fish, some serious protein denaturisation seems to occur. This is, along with the increased cost and complexity, probably what has kept this method from becoming one of the main standards instead of conventional water immersion thawing.

  The main pros of this method are:

    - Reduction in thawing times can be expected.
    - Less melting enthalpy and lower freezing point.
    - Less drip for most species.
    - Positive effects on microbial growth.
    - Extended shelf life with post-thawing pressure treatment.

  The main cons are however that:

    - The method is most likely more expensive than conventional methods.
    - Water binding ability of fish muscle is reduced during cooking.
    - Denaturalization of proteins, leading to lower sensory evaluation.
    - Not much experience on pressure thawing commercially.
    - Only seems to be applicable to fillets, not large blocks of whole fish.
    - Limited to batch thawing.

Unconventional Methods

To tackle the problem of uneven thawing of the fish and other products such as pork and beef, methods have emerged that involve generating heat inside the muscle or by somehow affecting the water molecules in the muscle without having to thaw the surface with conduction/convection first. These methods generally do not involve contact with a thawing medium. Variety of methods have surfaced that deal with this very problem, but the most notable ones are High Voltage Electric Field (HVEF) thawing, Ohmic thawing, microwave thawing and radio frequency systems. Vacuum thawing is also another method that cannot be categorized amongst the conventional methods, but still involves the usage of heat transfer through the surface of the products. These methods all involve unusual practises to carry out the thawing process and are usually much more expensive than the more conventional approaches. They have also, in general, not been developed to deal with large quantities which inhibits their introduction into the commercial market. These methods are not as widely used as the previously discussed methods and there is much less information available on them. The discussion on these methods will therefore not be as detailed as for the more conventional methods.

Vacuum Thawing

Vacuum thawing is a process which involves heat transfer through the surface, but cannot be considered as a conventional procedure due to its nature. During vacuum thawing, the fish is placed inside an air tight thawing chamber. The products are usually kept on racks or trolleys and therefore are usually not whole fishes or blocks; but rather fillets and smaller pieces. Vacuum is then drawn in the camber by a pump working through a suction valve. Figure 8 shows an example of such a chamber. Water is then let into the chamber in the form of heated vapour (Archer, Edmonds, & George, 2008). The water vapour condenses on the fish during the thawing procedure and this ensures that the coldest areas of the product always get sufficient thawing. By regulating the pressure inside the camber, the inside temperature, as well as the thawing rate can be controlled.

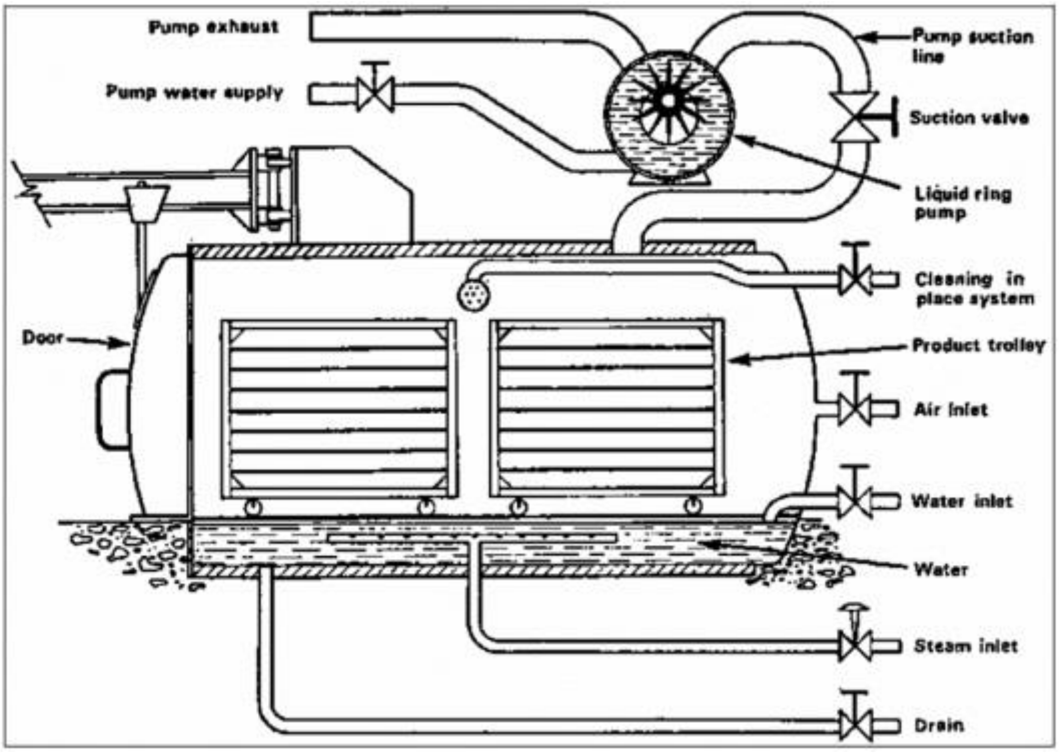

Figure 8: an example of a vacuum chamber used for thawing fish

This process is a thawing procedure that applies direct heat transfer through the surface of the product. As results, the fish products being thawed are in risk of getting uneven thawing, as with the conventional methods. This method is relatively hygienic and can be very efficient for small products with high surface area to volume ratio. Since the temperature is controlled by adjusting pressure within the chamber, it can be quite difficult to accurately control the heat transfer into the product. The main pros of the vacuum thawing technology are:

- Quick thawing for smaller types of products.
- Hygienic.

The main cons are however:

- Different programs for each type of food/products.
- Non-uniform thawing.
- Difficulties in controlling the product/ambient temperatures.
- Not very suitable for large quantities or batches.

Microwave Thawing

Microwaves are a form of radio waves in the electromagnetic wave spectrum. Their wavelength is usually of 1m down to 1mm or in the frequency of 300 MHz to 300 GHz. The spectrum which is used for television, cell phones and microwave ovens, for example, is called decametric, since it is in the higher regions of the wavelength band (0.1m to 1m). The frequencies often used for microwave heating are of 2.45 GHz.

When using microwaves to heat materials, the device is influencing the dipoles of the material being heated, such as the water molecule. The polarization of the molecule behaves in such a way that when electric field is applied, it starts to turn to face the same direction the electric field is facing. However, microwave ovens use alternating electric field so that the molecules are forced to change direction they're facing. There is a slight inertia in their turning, however, forcing them to lag behind the electric field. This forces the dipoles to start vibrating while resisting to the electric field, generating heat (Micro Denshi, 2016). Figure 9 shows an example of an industrial microwave thawing unit from Ferrite Microwave Technologies (Ferrite MT, 2016).

Figure 9: Industrial Microwave Thawing unit from Ferrite MT (MIP10)

Microwaves can however only penetrate a certain amount of material at once, which can therefore result in uneven rate of heating throughout the material being thawed/tempered. That is the reason for why many companies that are working with large volumes of products, such as meat and fish, have resorted to industrial tempering with microwave technology;

rather than completely thawing the products. The products or raw materials are then tempered towards a desired temperature, typically in the range of -2 to -5°C. Figure 9 shows a batch industrial thawing unit from Ferrite Microwave Technologies, but they offer various solutions for food producers; either for the purpose tempering, cooking or drying their products, both on batch and continuous basis. Figure 10 shows Ferrite's flagship continuous tempering unit, capable of tempering around 7700 kg of products per hour. These special built systems are quite expensive, so only companies with a strong financial basis can consider investing in these types of solutions. Microwaving is a quick method for tempering and is as such an interesting solution for companies with high throughput and strong financial basis. Another advantage of microwaving is that it is very hygienic and does not use any water or air injection, which therefore eliminates the need for a special filtration systems. Minimal drip loss has also been reported for microwave tempering/thawing.

Figure 10: Ferrite's continuous industrial tempering unit

AS microwaving produces uneven rate of thawing, it is usually just applicable for smaller quantities consisting of small units i.e. if the intention is to thaw the material completely. Even with relatively small lots of fish, the outer layers can become overheated and cooked before the centre is completely thawed. Furthermore, for products in the middle of the thawing process can experience what is called runaway heating. What that means is that the parts of the material that is already thawed absorbs energy more easily than those still frozen, which slows the thawing process significantly down.

Microwave thawing has some definite advantages, but the technology does also have its weak points, as discussed above. The min pros of microwave thawing are:

- Heat is generated in the product.
- Quick for tempering purposes.
- Minimal drip loss reported.
- Very hygienic.

The main cons are however:

- Very high initial and maintenance cost.
- Uneven rate of thawing.
- Can be difficult to control.
- Usually only applicable for smaller quantities at once, even though large systems do exist.
- Specialized equipment requires specialized maintenance crew.

Radio Frequency Systems

Coming directly from microwave technology, it is appropriate to mention radio frequency systems next. Microwaves are a part of the radio wave spectrum, so these two methods both involve stimulating the dipole characteristics of water molecules. Radio frequency thawing systems operate however at lower frequency, allowing for a more uniform thawing of the products towards 0°C. These systems are available both as batch thawing units (smaller) to continuous thawing units (larger).

The products that are to be thawed are placed between two parallel electrodes, while alternating radio frequency is applied. Thawing rates are relatively uniform, though dependent upon the size and composition. Products being uniform in shape are more easily thawed using this method than irregularly shaped objects. The companies Sairem and Stalam, which are located in France and Italy, are among companies offering radiofrequency thawing units for the food industry.

As with microwave thawing, the time needed to thaw the product is substantially shorter than with more conventional methods. Typically, it will take 35-40 minutes to thaw a block of meat from -20°C to -4°C when using this technology. A continuous RF thawing unit from Stalam can be seen in figure 11, but this machine has a thawing rate of 1250 kg/h.

Figure 11: Continuous RF thawing unit from Stalam

The pros and cons of this method are very similar to those of the microwave thawing units, but the main difference is the rate of thawing. The main drawbacks lie in the frequencies of the waves being transmitted into the products. RF thawing uses lower frequencies that are capable of more easily impact the whole product, whilst microwaves only reach as far as a specified distance into the dielectric medium being thawed (Archer, Edmonds, & George, 2008).

Limited research have been conducted on quality issues connected with RF thawing. That is research field that will undoubtedly be given more attention in the near future.

RF thawing has its advantages and disadvantages, as with all thawing solutions. The man pros of this technology are:

- Heat is generated in the product.
- Quick heating and tempering.
- Minimal drip loss reported.
- Very hygienic.

- Not much reported on loss of quality parameters, which may indicate that not being a major problem.

The main cons are:

- Very high initial investment cost and maintenance cost.
- Can be difficult to control.
- Specialized equipment requires specialized maintenance crew.

High voltage electrostatic field (HVEF) thawing

HVEF thawing could easily be confused with radio frequency thawing methods, as both technologies involve the product being placed in between parallel plates. However, while microwave and radio wave technologies involve stimulating the molecules of the frozen material directly by the waves themselves, HVEF methods involve creating electrostatic fields around the products by applying high voltages to two parallel plates. The gap between the two plates is of great importance and has been shown to impact the thawing rate of frozen tuna (Mousakhani-Ganjeh, Hamdami, & Soltanizadeh, 2015). The typical voltage levels can be from 2-15 kV, but thawing times have been shown to decrease with increasing voltage applied to the plates. A simple schematic of a standard HVEF thawing unit can be seen in figure 12.

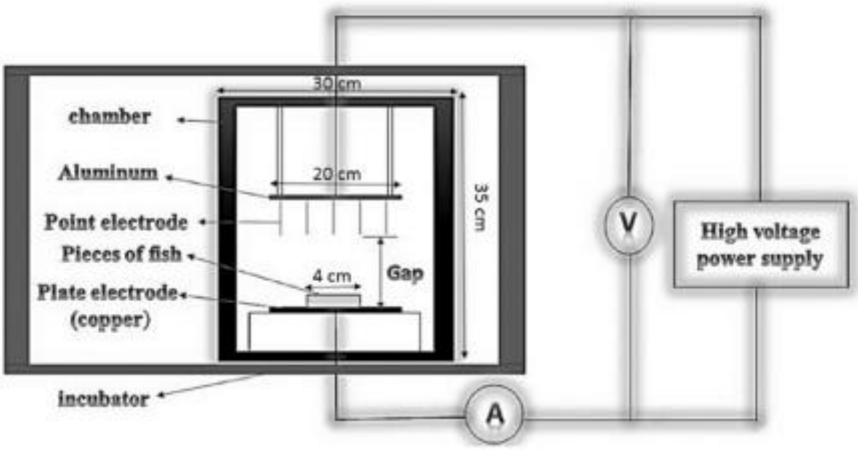

Figure 12: Standard HVEF thawing unit

HVEF thawing has similar drawbacks the high pressure assisted thawing methods, as the proteins contained in the fish muscle seem to be greatly affected by the electric field. Minimal drip loss is measured during the thawing process, but the water drains out much more easily during cooking. This does not happen with the standard conventional methods. This denaturalization of the proteins therefore affects the water holding capacity of the muscle after thawing, leading to water loss under cooking. Texture and colour changes were also observed in thawed tuna samples tested, leading to lower sensory values compared to conventionally thawed samples (Mousakhani-Ganjeh, Hamdami, & Soltanizadeh, 2015).

Despite the fact that the proteins are seemingly affected by the electric field, the total volatile basic nitrogen levels (TVB-N) have been reported to be significantly reduced with higher voltage applied to the plates. These levels are known to cause decay in fresh products under storage and any reduction in those values therefore should improve the storage. However, the reduction in these numbers could also indicate the former denaturalization of already available proteins in the muscle.

HVEF thawing methods have not be used at industry level for thawing blocks and large quantities of fish, but have rather been focused on fillets and smaller samples. That might however change in the near future, as research undoubtedly increase and more refined equipment produced. A key research field will be to address the denaturisation of proteins.

There are definite advantages and disadvantages associated with HVEF thawing. The main pros are:

- Dramatic reduction in thawing rate/times.
- Reduced levels of volatile nitrogen levels (TVB-N).
- Thawing rate/times can be controlled effectively with voltage and electrode gap.
- Very hygienic.

There are some various cons as well which up to this date still outweigh the pros by some margin regarding the overall quality of the product, especially after cooking. These include:

- Considerable reduction in water holding capacity during cooking.
- Colour reduction of samples.
- Negative changes in texture.
- Protein denaturisation.
- New and expensive technology relying on sophisticated equipment.
- The technology has not been used at industry scale for large quantities nor whole fish, but rather for small samples.

Other new or less used methods

There are other methods available for thawing frozen food products, but they are not nearly as widely applied as the methods already identified in this report. Some of them are just starting to be explored. These methods have not been presumed likely to cause a breakthrough in the field. The main problems with these approaches are that they are either too complex in design; costs are way too high and/or they can only operate on small quantities at once. These methods are therefore not really alternatives that industry scale seafood processors can consider at present. We would tough like to identify two of these technologies as example.

Electrical heating

Electrical heating is, in practical applications, very similar to HVEF and RF thawing methods. The products are placed in between two parallel plates that touch the material directly. Alternating voltage is then applied and with sufficiently uniform material and even contact with the parallel plates, heat can be generated in the product. The voltage and frequency greatly impact this heat generation. This method is however only applicable for uniform products that maintain their composition and shape during thawing, as uneven contacts with the plates can cause localised heat generation and subsequently result in overheating.

Climatic thawing systems

Climatic thawing systems are units that very interesting solutions that are increasingly being used to thaw fish fillets. The fillets are placed inside the units, which are computer controlled and monitored for temperature and humidity.

The systems are capable of monitoring the core temperature of products and are therefore able to determine when sufficient thawing has been carried out. The chambers then adjust the conditions to temper and cool the products down to storage temperatures when thawing has fully been carried out. These systems are at the moment not designed to thaw blocks of whole fish or large volumes necessary for industrial seafood processors.

Summary and discussion

The most common methods and technologies for thawing frozen fish have been identified and discussed in the report. The focus has been on discussing practicality and applicability in regards to thawing whole fish for further processing. The most commonly used methods include immersing the frozen fish into water that is temperature controlled. This is a solution that is relatively simple, affective and inexpensive. More sophisticated methods include using microwaves, radio waves and climate controlled chambers as example. All the approaches and technologies discussed in the report have their advantages and disadvantages. It is therefore difficult to recommend any solution over other, as technologies that fit one sort of producer will not necessarily be suitable for the next one. Fish processors will therefore have to evaluate the pros and cons of each technology and decide what is best for their setup, species, products and throughput.

The most basic considerations when thawing fish is the importance of keeping the products or raw materials as close to the freezing point of water as possible. Temperatures reaching too high above 0°C can stimulate growth of unwanted bacteria and damage the muscles. The temperatures of the thawing medium should therefore be closely monitored at all times. After thawing the fish must be given a chance to temper and reach even temperatures throughout the whole volume. Furthermore, storing the fish under or very close to 0°C is then important as thawed fish is just as quick, if not quicker, to lose its material quality as a fresh fish. Using water based methods should only be done to whole or partially processed fish, as water thawing fillets will make them soft and can reduce their quality. Furthermore, when thawing with water, the medium has to be filtered regularly or substituted for a new thawing medium since blood, bacteria and other contamination factors can easily travel between samples being thawed.

The thawing times should be well thought out, as spending too much time thawing the products can decrease their quality. Thawing times of under six hours can be considered satisfactory though too quick thawing times can also be dangerous. Applying too much heat into the product too quickly can cause localised heating and uneven cooking on some occasions.

This report has only covered the most commonly used thawing methodologies and a selection of new and novel approaches. This is therefore not an exhaustive coverage of all available thawing methods. The same applies to individual solution providers, as the report has only identified selected few manufacturers of thawing equipment. The discussion on the thawing equipment should however provide a good indication or a cross-section of what is available.

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