Application of water jet cutting in processing of cod and salmon fillets

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HÁSKÓLI ÍSLANDS

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Abstract

The focus of the study was to establish knowledge on water jet cutting of fish that could be utilized in the design of FleXicut. FleXicut is a water jet cutting technology developed for white fish with focus on cod. Is able to cut different shapes and curve cut. The relationship between water jet cutting conditions, fish species, physical properties and temperature of fish fillets was studied. Cod and salmon fillets were tested by applying different precooling methods and the fillets cut either with or without skin. The main criteria for success in water jet cutting were the cutting efficiency and edge quality, including if the water beam was able to cut through muscle, connective tissue and skin.

The results showed that the transverse speed (cutting speed) was the most important factor when it comes to quality of cut since saw dust (saw mince) increased in fillets with increasing transverse rate. The connective tissue was the main problem in the tail portion of the fillet for cutting efficiency especially for cod fillets. Super-chilling prior to cutting resulted in better cutting and less saw dust. It was more important for salmon fillets compared to cod fillets regarding skin cutting quality and through the tail cut, if the fillets were superchilled.

KEYWORDS: Water jet, FleXicut, super-chilling, x-ray, transverse speed, saw dust, orifice diameter, pressure, connective tissue, cod, salmon

Ágrip

Markmið þessa verkefnis var að safna upplýsingum við vatnsskurð á fiski sem nýtt var við hönnun á FleXicut. FleXicut er vatnsskurðartækni þróuð fyrir hvítfisk með áherslu á þorsk. Hægt er að skera mismunandi mynstur og beygðan skurð. Samband milli vatnsskurðarskilyrða, fisktegunda, eðliseiginleika og hitastigs í flökum voru rannsökuð. Þorsk- og laxaflök voru prófuð með því að nota mismunandi forkæliaðferðir og flök skorin annað hvort með eða án roðs. Árangur við skurð var metin út frá gæðum og hreinleika skurðar, þ.m.t. hvort vatnsbunan náði að skera í gegnum vöðva, bandvef (sinar) og roð.

Niðurstöður sýndu að skurðarhraði skipti hvað mestu máli þegar kemur að gæðum þar sem salli eykst í flökunum við aukinn skurðhraða. Bandvefurinn var aðalvandamálið þar sem erfiðast hafi verið að ná að skera vel í gegnum sporð í þorski vegna bandvefs. Með því að undirkæla flökin fyrir skurð skilaði sér í betri skurði og minni salla í flökunum. Þetta skipti meira máli fyrir laxaflök í samanburði við þorskflök þar sem gæði skurðar gegnum roð voru mun betri, ef flökin voru undirkæld.

LYKILORÐ: Vatnsskurður, undirkæling, röntgen, skurðhraði, salli, spíssastærð, þrýstingur, bandvefur, þorskur, lax

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At last I want to thank my lovely family and boyfriend for all the support and patience throughout my studies.

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1 Introduction

Technology is always changing and new and better machines are being developed to make the industry more automotive. In the field of fish processing, technology is a big part of the processing making the process faster and by having machines that are able to cool the product better, quality and hygiene can be maintained. The world is also changing from impacts from economic crisis, climate changes, and increase in population. The food industry and nutritional level in the world must meet this challenge, and the question is how?

In recent years, there has been a rising demand for fish and fishery products in the world and the increase in the trade markets in this area is also growing. One of the main reasons for this increase in consumption and popularity is the increase in recognition of seafood and its compounds as a factor for improved human health. According to the world review of fisheries and aquaculture, supplies of captured fisheries and aquaculture was about 137 million tonnes in 2006 of which of 114 million tonnes were for human consumption (about 79 % of the total world fisheries). In the last five decades there has a sustained growth in fish production and products are handled and transported by highly efficient distribution channels to ensure that the integrity of the product is maintained. The increasing growth and improvements in distribution channels has led to dramatic growth in world fish supply in the period from 1961-2009 (Table 1.1) (FAO, 2012). Of this 114 million tonnes used for human consumption in 2006, about 57 million tonnes were used for direct human consumption. About 50-70% of the fish might results in by-products has the filleting yield can range from 30-50 % in operation (Karlsdottir, 2009).

In the world, China is the top producer in total capture fisheries where marine fish products account for more than 90% of the world capture fisheries production and the rest being fresh fish from farming (FAO, 2012).

Table 1.1: The production and utilization of the world fisheries and aquaculture (FAO, 2012)

(*Million tons*)	2006	2007	2008	2009	2010	2011
PRODUCTION						
Capture						
Inland	9.8	10.0	10.2	10.4	11.2	11.5
Marine	80.2	80.4	79.5	79.2	77.4	78.9
Total capture	**90.0**	**90.3**	**89.7**	**89.6**	**88.6**	**90.4**
Aquaculture						
Inland	31.3	33.4	36.0	38.1	41.7	44.3
Marine	16.0	16.6	16.9	17.6	18.1	19.3
Total aquaculture	**47.3**	**49.9**	**52.9**	**55.7**	**59.9**	**63.6**
TOTAL WORLD FISHERIES	**137.3**	**140.2**	**142.6**	**145.3**	**148.5**	**154.0**
UTILIZATION						
Human consumption	114.3	117.3	119.7	123.6	128.3	130.8
Non-food uses	23.0	23.0	22.9	21.8	20.2	23.2
Population (*billions*)	6.6	6.7	6.7	6.8	6.9	7.0
Per capita food fish supply (*kg*)	17.4	17.6	17.8	18.1	18.6	18.8

Fish is one of the key industries in Iceland that forms the backbone of the society. The economy in Iceland is also more or less based on fishing and fish processing. By saying so the processing and the techniques that are used in this area are very important. The world of techniques is always changing and the demand from consumers for fresh and high quality fish products is always increasing in the developed countries. In fish processing the goal is to get the maximum utilization and receive the best product quality. The rest material and discards in fish processing can count up to three-quarter of the total weight of the fish. Processing yield depends highly on the fish species and how the fish is caught e.g. fish caught on trawler normally has higher filleting yield than line fish. In fish processing the rest material and discards account for almost three-quarter of the catch total weight. With new and better technology new bioactive compounds may be processed from rest raw material that can bring more value from waste (Figure 1.1) (Arason *et al.* 2009).

Today many different types of techniques are used to process fish and water jet cutting is one of them. Although the use is limited still, people are optimistic that it will increase processing yields, result in higher product's price and increase automation.

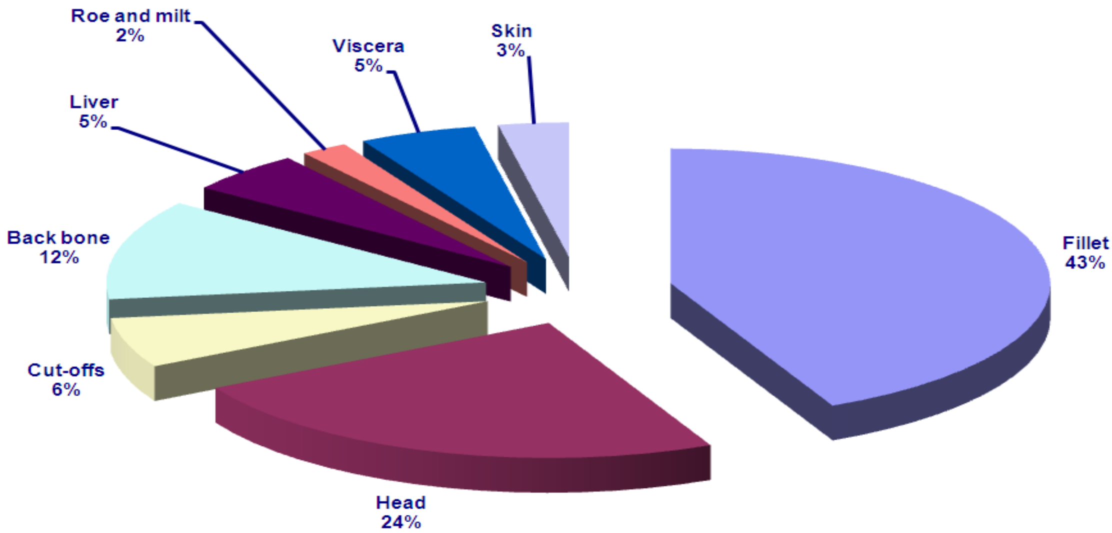


Figure 1.1: Fish products and rest raw material from processing of ungutted cod (Arason et al. 2009)

Fish is broadly classified into finfish and shellfish, which are then divided into other categories. In the study, the focus will be on finfish. There are many different fish species that are categorized under the finfish which are then divided into either lean fish or fatty fish. These two categories are distinguished by terming lean fish that store lipids in the liver and fatty fish that contains lipids throughout the fish flesh. In this study, the focus will be on cod that goes under round lean fish along with haddock, hake and pollock and otherwise salmon that is an oil-rich fish along with fish species like mackerel, herring and trout (BIM, 1999).

Studies on fish and fish processing have shown that temperature control is very important to ensure fish quality and shelf life. In fish processing, it is important to apply rapid cooling after catch, maintain low temperature and prevent temperature fluctuations in the fish. It is also important to ensure that the temperature in fish fillet will not go higher than 4°C which would increase the risk of bacterial contamination tremendously. Most countries that are involved in fishery sell their fish both domestically and export it to other countries. In Iceland for example, the fish is exported to other countries continually, which means that the shelf life needs to be long and the temperature and the quality of the fish products need to be carefully secured.

The fish processing can vary in terms of operation and production. In most processing lines, the following operations are involved: heading, cutting if needed, filleting, (skinning) and trimming. Sometimes, precooling is applied before skinning, for example by using SuperChiller (by Skaginn ltd.). Manual trimming occurs after the skinning process, where fillets are cut by knife into portions and remaining bones removed along with blood spots etc. Finally, the products are inspected to ensure that the product standards are met, packaged and shipped. With the advent of water jet and x-ray the processing line will change by substitute manual trimming for water jet cutting and adding x-ray technology prior to the water jet cutting. The automation of pin bone removal, for example by water jet cutting will lead to changes in the process. Pre-trimming directly after filleting may be one of the options, prior to skinning and water jet cutting x-ray will be used for bone detection and determination of fillet geometry before entering the water jet where bone removal will occur. Portioning and trimming may also be conducted by the water jet cutting machine, depending on the production. Finally, the products will be inspected to ensure that market requirements are met, and then packaged and shipped (Figure 1.2).

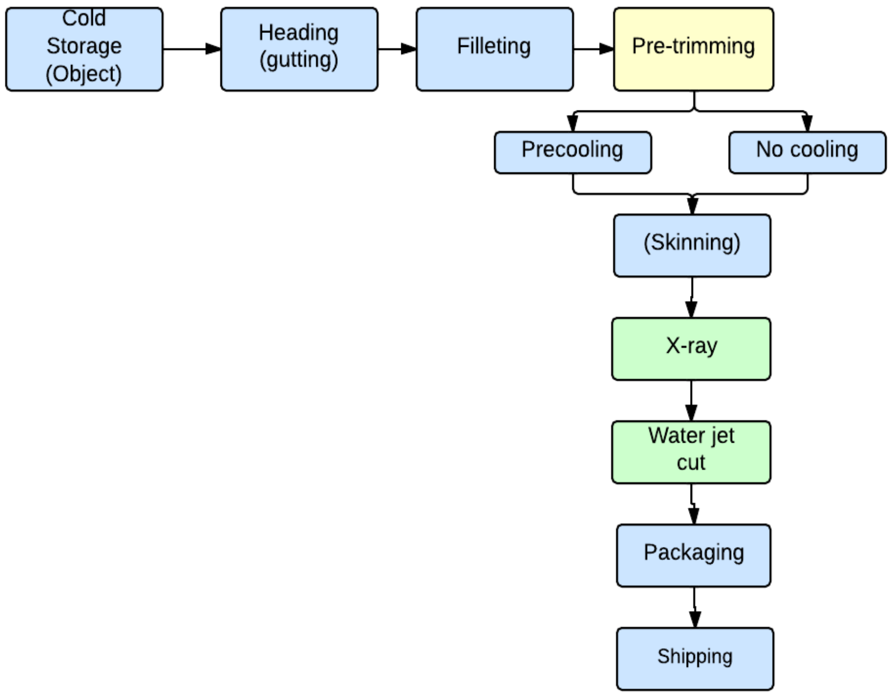


Figure 1.2: Flow chart of possible future process with the advent of x-ray and water jet

Objectives

The overall aim of the study was to test different variables in water jet technology that Marel has been developing during the last couple of years. The water jet cutting used for the design of FleXicut was developed for white fish with focus on cod, which is able to cut materials with different shapes and curves. The specific objectives of this work were to:

- To establish knowledge on water jet cutting of fish that could be utilized in designing FleXicut.
- Explore the main criteria for success at water jet cutting like cutting efficiency and edge quality
- Study the relationship between water jet cutting conditions like transverse speed (cutting speed), pressure, orifice size and stand-off distance of the orifice, and success
- Investigate the effect of fish physical properties (different part of the fillets), species (cod vs. salmon), fillet size, along with fillets with and without skin on success
- Investigate the effect of temperature of the fish fillets, using super-chilling (pre-cooling) fillets in comparison to untreated fillets on success
- Determine the optimum running conditions for water jet cutting

The anticipated results were information about how the water jet technology works and input during the mechanical design of FleXicut. The aim was to establish a water jet system that is able to remove pin bones, cut the fish fillet into portions along with some trimming in such a way that cross contamination will be minimized since the water jet uses no blades and increase the product value by increasing utilization. The FleXicut will lead to more continuous flow compared to manual cutting so the production can be controlled in better way leading to fewer delays in the process. The temperature in the water jet can be controlled compared to manual cutting, which led to safer and increase in shelf life. The FleXicut will lead to more automation in pin bone removal, portioning and trimming.

2 Background

This chapter includes scientific background of this study. Water jet technology will be discussed and advantages the technology has over conventional cutting. Superchilled and cooled fillets will be tested to see how the cooling affects the water jet cut. Bone detection system used in the water jet process will be described. Finally, the material properties of the two species cod and salmon used in these experiments will be discussed.

2.1 Water jet technology

Since early 1960 water jet technology has been developed and today this tool is used in a variety of industries. The water jet cutting is available in one-, two-, or three-dimensional and robot applications. The two-dimensional is most widely used and the system includes high transverse speed and is able to cut larger parts at the same moment. The one-dimensional cuts web material and is used in multi-shift operation with high transverse rate. The robot application is used with the three-dimensional cutting which has a cutting head installed to the arm of the robot that goes along with the three-dimensional piece for cutting holes and trimming the material (KMT, 2008).

Basically, there are two main types of water jets; (1) abrasive water jet and (2) pure water jet that are designed to employ only abrasive water jet, only water water jet or containing both. For the pure water jet technology, the processing capability is limited so often abrasive particles are added to the water, like sugar and salt to form abrasive water jet (AWJ). The AWJ technology has many advantages over other conventional technologies, such as high flexibility that gives it the ability to cut in all directions, high cutting flexibility to cut almost any material with no thermal effect on the cutting material and process efficiency is high (Wang & Shanmugan, 2007). The pure water cutting only uses pressure and water to cut the material and is mostly used to cut material like food and rubber (KMT, 2008). There is a difference between the nozzle for pure water jet and abrasive water jet. The pure water jet nozzle has no opening or mixing tube so the high-pressure water is directed to the material after it exits the jewel. The abrasive water jet on the other hand has an opening in the side of the nozzle which allows for the introduction of the abrasive to the high-pressure water steam (Water jet.org, 2014).

The water jet technology pump is used to generate high pressure of water which then passes through the orifice and nozzle that forms the high pressure water jet (Wang & Shanmugan, 2007). For the nozzle and head design of the water jet the water is lead through an orifice that can be either a diamond orifice or ruby sapphire. It depends on whether it is for abrasive water jet or just water applications. The diamond orifice is used when abrasive might be used. These water jets normally have diameter between 0,2 and 0,4 mm. The water goes into the nozzle made of tungsten carbide that normally has the diameter of 0,5 to 2 mm. The diamond orifice can also be used for pure water jet to have better particles to prevent particles that could come with the water that can damage the orifice. It depends on the type and the material of the nozzle how long it can last, but for the normal nozzle it can be up to 100 hours when the application is used for cutting with 150-300 µm (Figure 2.1) (Folkes 2009).

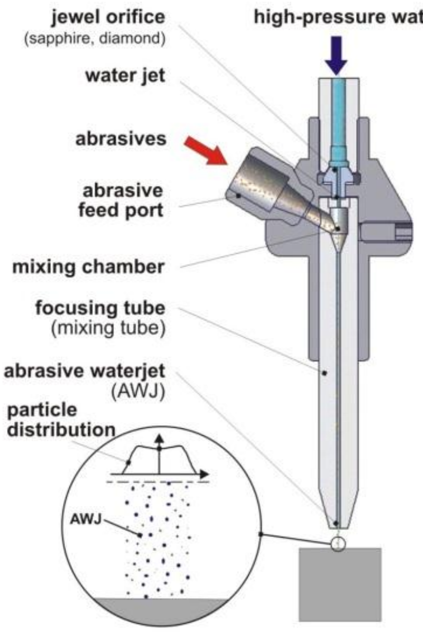


Figure 2.1: Schematic construction of a cutting head for abrasive cutting (Water jets, 2013)

The water jet is made from three regions, initial-, main-, and final region (Figure 2.2) (Yanaida & Ohashi, 1980). Stagnation pressure in the initial region is believed to be the same as the nozzle exit and in the main region the velocity of the axial is believed to be constant. In the final region there is a decrease in water droplets where the droplets break up into finer droplets. Two types of pressures are formed from the contact of water with the target material, stagnation pressure and hammer pressure, which are responsible for the work that the water jet does to the target material. These pressures occur at the point of the impact. When the continuous jet hits on a solid material the stagnation pressure is generated at the impact point. The hammer pressure is generated at the instant of impact when water lump or droplets hits on a solid material. Under ordinary impact condition the stagnation pressure is much smaller than the hammer pressure (Shimizu, 2011).

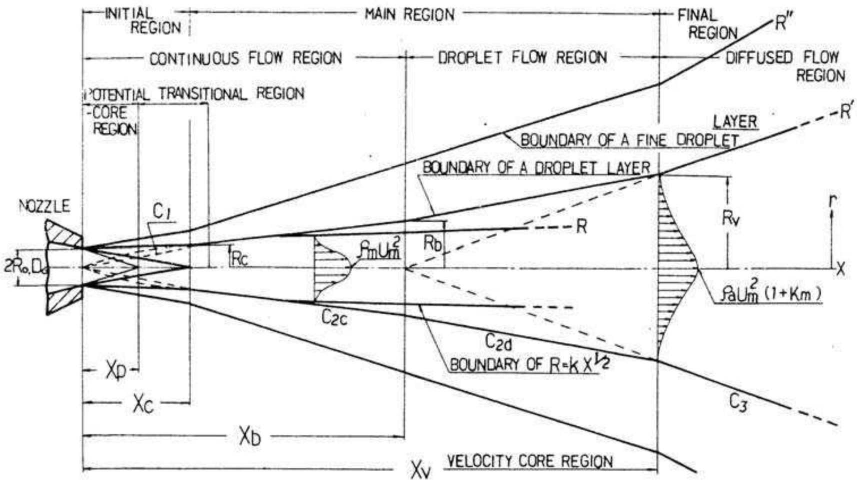


Figure 2.2: Schematic diagram of water jet in air (Yanaida & Ohashi, 1980)

The size of water jet system needed is determined by two factors, the water volume and pressure. There are three variables that are crucial when it comes to determining how much water and pressure are needed: The type of material, transverse speed required and the size and number of cutting heads. The type of the material is crucial when it comes to the water jet cutting like the thickness and hardness that determine the minimum amount of water volume needed. The thickness of the material is important where it requires larger steam of water that results in more energy to cut over a long distance. The hardness of the material determines whether to apply abrasive cutting or pure water. The transverse speed is important for the cleanness and the quality of the cut and by increasing the transverse speed is also important for high production environments. The transverse speed is based on the pressure applied, the thickness of the material, the shape of the cut and the number of orifice diameters needed that result in good quality cut. The water consumption depends on the number and size of orifices. The use of used multiple cutting heads more water is required permits higher productivity (KMT, 2008).

The water jet process can occur at transverse speed with high water jet pressure. The range is: pressure from 1,300 to 6,200 bar (18,870 psi-90,000 psi) and from 50-1100 mm/s in transverse speed. Conventional water jet cutting operates at pressure of 4,100 bar and is mainly used for cutting softer material and is suitable for the food industry. By using pressure up to 6,200 bar, which is the highest operation pressure, can lead to higher productivity, optimized machine utilization, improved conformity and reduced delamination (Folkes 2009). This high water jet pressure eliminates drop of pressure and enables twice the cutting power over the 4,100 bar water jet system that results in maximum performance and power, increase in productivity, lower consumption of abrasive compared to lower pressures applied and the fastest cutting. This high pressure is mostly applied to cut very hard and thick material like thick steel, aluminum, brass and titanium and has the ability to increase the maximum of the pressure range and transverse speed up to 50% (Casey, 2011).

2.2 Water jet applications in the food industry

The water jet has in the recent years received acceptance for cutting food material both processed and unprocessed. Water jet cutting has changed the way foods are cut and packaged. Many foods, from fruits and vegetables, pizza and delicate pastries to meats can be elegantly cut using a water jet. The water jet can cut intricate shapes to a high precision quickly and economically. The water jet technology is growing fast in the food industry mainly because of high transverse speed, time saving and hygiene. Since the water jet uses no blades, the risk of cross contamination will be minimized that result in better and saver product (KMT 2008). In order to obtain good results for cutting fish fillets of different species, size and thickness, the transverse speed, orifice diameter, water jet pressure, and stand-off distance have to be specially matched (Bansal & Walker, 1999). The state and firmness of the material are also important when it comes to the water jet cutting to obtain the best quality and utilization of the material. It is important to handle the material in the right way, e.g. by applying precooling techniques before cutting (section 2.5).

The water jet has very good mobility and the flexibility is unique. The technique is able to cut at lower temperature compared to manual cutting, has more continuous flow, automation like pin bone removal, portioning and trimming, the cross-contamination is minimized, and has higher product value. With these advantages the machine is able to cut better compared to other techniques. The main reason is because of more flexibility in the cut, and potential curved cut that cannot be obtained with the knife. The water jet contains no blades and tools that are in contact with the food that minimizes the risk of bacterial transmission. The water jet is able to cut wide range of material with high accuracy, and no heat affected zone, meaning that the water jet does not heat the product (part) and does not change the properties of the material (Waterjet.org, 2014). No chemicals and radiation are used in the process. The water jet can work with almost any material, even material that are heat-sensitive and is becoming more important in the field of food processing. The water jet offers many advantages over other conventional methods for cutting, like milling machine, flame torch or band saw. These advantages include increased cutting speed, more continuous flow, cutting at low temperature compared to manual cutting, higher product value, able to cut variety of material and thickness and no blade wear used (Casey, 2011).

The water jet transverse speed is very important for fish production and depends on many parameters, specially the thickness of the material, the size of the species, and the water jet pressure. Cutting with low transverse speed shows no visible striations and the water enters and exits the material at the same point. It is important to increase the transverse speed in the process to higher the productivity, which led to more profit for the company (Shimizu, 2011).

It is predictable that the water jet cutting will become a dominant factor in the food industry. Advantages like safety, flexibility in cut, cost, effectiveness, hygiene and process adaptability far outweigh the current limitations (Calabrese, 2011).

2.3 X-ray

Marel has developed a bone detection system that automatically finds bones in the product. The system scans the product fillet that is tested using advanced x-ray technology and sends feedback on rate of bone content. If bones are found it is rejected to a workstation that shows the location of the bone. The x-ray is able of detecting bones of various types and sends signal to reject it, but it depends largely on the size and thickness of the sample how well it detects the bones. It is able to detect bones to a certain size limits (larger than 2 mm). The x-ray can also detect other things like glass, stone, and metal which makes this technology even more important for food processing (Marel, 2013).

For the design of FleXicut the x-ray will be used to locate the bones with high accuracy and to control the cut. Work has been done on improving the diagnostic accuracy making the x-ray being able to locate smaller bones and develop the algorithm.

From testing's in Dalvik senorX machine was able to locate 60-77% of all bones with the size of 35-50 cm. Bones that were bigger than 0.3 mm were observed in 91-100% cases (Sigurjónsdóttir, 2009).

2.3.1 Bones - detection limits

In the fish industry, detection of bones is normally done manually by using sense of touch or visual inspection. Using mechanical or electrical method for bone detection will result in better quality control in fish industry. According to Whitney and Officewala (1982) what should be referred to as bone and what is a "non-bone", a bone that is less than 10 mm long and less than 3 mm in any dimension is disregarded as bone. Bone that is greater than 40 mm long and 10 mm in any dimension is referred has critical bone, and bone that exceeds the 10 x 3 mm limit but less than 40 x 10 mm limit should be referred as a bone defect.

2.4 Material properties

Fish can be sold in many different ways as raw material products for further processing or consumers products: whole ungutted fish, gutted fish, steaks and cutlets, butterfly fillet were the flesh is cut from both sides of fish, and single fillet where slice of flesh is removed from one side (BIM, 1999). To receive the best quality of the fish it needs to be unspoiled and fresh and when it is consumed it will retain all the characteristics of the flavors of the species.

The present thesis focuses on cod (*Gadus morhua*) and Atlantic salmon (*Salmo salar*) that are both available as wild and farmed fish and are economy important fish species. These two types of fish are both bony fishes and have rather equal right and left fillets but are quite different in chemical composition. The water and fat content for both cod and salmon ranges and is quite variable between fishes and even for the fishes in the same species.

For both cod and salmon, the water content is high and ranges from 80 to 83% for cod and is a little bit lower for salmon 64 to 71%. The protein content in the muscle is rather similar between these two species, i.e. around 20%. The lipid content is quite variable between species. Cod is a lean fish with lipid content less than 1% compared to salmon with lipid content 13-15% (Table 2.1). The water and lipid content constitutes approximately 80% of the total body weight of most fish species. These compositions can be different between fishes within the same species and also different parts of the fillet due to the age, size, sexual maturation and nutritional level in the fish (Hultmann, 2003). The water and fat content is quite variable between these two species and the fat also depends on whether the fish is farmed or from wild stock.

According to Tommeras the lipid content of the farmed Atlantic salmon can range from 7-17.2% while the total lipid content of wild Atlantic salmon can range from 0,2 up to 9.7%. These differences may be explained by the nutritional status of each individual. The variation in the wild salmons can may due to individual feed excess or appetite.

Table 2.1: Chemical compositions of salmon and cod muscle (Hultmann, 2003) (Tommeras, 2011)

Composition	Salmon	Cod
Water	64-71%	80-83%
Protein	20-22%	15-20%
Lipid	13-15%	0.5-0.8%

The fish muscle is mainly composed of myofibrillar proteins. Actin (thin filament) and myosin (thick filament) are the main proteins that compose the myofibril which are arranged into thick and thin filaments (Brenner, 2009). Fishes that have bony and cartilaginous muscles contain about 2-5 % and 11% connective tissue, respectively. There are two kinds of fish muscle, dark muscle and light muscle. In white fish like cod there is a small strip of dark muscle on both sides under skin of the body. In fatty fish like salmon the strips of dark muscle are much larger in proportion and contain higher concentration of certain vitamins and fat. The diagram of cod fillet (Figure 2.3) shows mechanical construction of typical white fish with blocks of muscle that are separated by thin sheets of connective tissue that are curved within the fillet and goes from the backbone to the skin. In each of the myotome the muscle fiber run parallel to each other giving the movement needed for swimming during contraction. The muscle fibers are shorter towards the tail than near the head of the fish and the connective tissue in the tail portion is several times larger than the head (Hultmann, 2003).

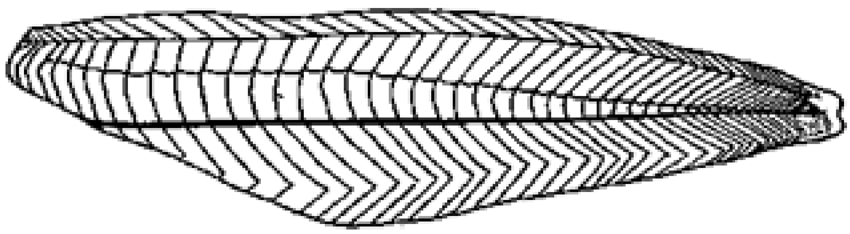


Figure 2.3: Diagram of mechanical construction of typical white fish (Murray et al. 2001)

In fish, the muscle proteins can be divided into three groups: water-soluble, salt soluble and insoluble proteins. Fish muscle has high level of salt soluble or myofibrillar proteins and not so much of insoluble proteins in comparison to muscle in land animals. The myofibrillar proteins are important for the water-holding properties and the texture of the muscle of the fish species (Hultmann, 2003).

One of the most important quality parameter is the texture of the fish. The texture can be influenced by several factors, like the age, size, fish species, fat content, quantity and properties of proteins and connective tissue, stress before slaughter and handling of the fish. Post mortem factors, like rigor mortis the level of pH drops, breakdown of connective tissue and myofibrils, rigor mortis along with temperature during the storage time (Huss, 1995).

2.4.1 Cod

Cod is the most important commercial fish in the North Atlantic. The fish species that has given the most value to the Icelandic economy through the years. Cod is a ground fish that lives from few meters down 600 meters depth where temperature is around 0-12 °C. The temperature can be variable due to season, ocean, and location. The fish is about 30-60 cm long and can reach up to 25 years of age. Cod is caught with variety of gears: line, net, bottom trawl, hand lines, and seine and the age of fish is usually 4-7 years. In recent years, the cod catch has been about 150-470 thousand tonnes each year that gives the average of 270 thousand tonnes per year. The handling of the fish material from the catch to the final product is very important for the quality and value of the material. Factors like the catching method, handling after catch, cooling method, storage container, storage time, and type of icing are all factors that determent that (Matís, 2010).

The cod fish can be prepared in different ways: wet whole gutted, fillets with or without skin and cutlets or steaks, and processed as smoked primarily done to give the fish appetizing flavor and appearance, or salted and dried. The cod fish can be consumed raw, cooked or smoked (BIM, 1999).

2.4.2 Salmon

Atlantic salmon (*Salmo salar*) are found in the North Atlantic Ocean, from Iceland and southern Greenland, from Artic circle to Portugal in the eastern Atlantic both on the North American and European sides along with North Atlantic islands, and from Ungava region of northern Quebec south to the Connecticut River (Figure 2.4) (Renzi, 1999). The salmon can be prepared in different ways wet, whole, gutted, fillets, steaks or cutlets, boneless skinless fillets or smoked (BIM, 1999). In recent years there has been an increase in salmon consumption due to positive health benefits from consumption of oil rich fish. The demand for salmon for human consumption as increased in recent years, which is associated with the positive health benefits with the consumption of oil rich fish. In order to obtain the best quality of the fish, factors that can affect the quality, need to be avoided.

The Atlantic salmon is the dominant cultured species with a production volume of 1.5 million tons in 2008 (FAO, 2010). The increase in demands for fish meal and fish oil has exceeded the supply and about 50 % of the Atlantic salmon that is consumed worldwide is from of fish farming (Tommeras, 2011).

Figure 2.4: Main producer countries of Atlantic salmon (Salmo salar) (FAO Fishery Statistics, 2006)

2.5 Precooling techniques

The temperature of the food product is the main factor when it comes to quality loss and shelf life of fresh food. The most important method for preservation and distribution of food products the world market is by chilling and freezing the product (Magnussen et al., 2008). To receive the best product and controlling spoilage the fish should be chilled down to 0 °C so enzymatic and bacterial activity will be minimized. By this, shelf life in the fish can be extended, but this temperature needs to be maintained during the whole process, storage and until it goes to the consumer. This can be done by using ice which melts at 0 °C that will then chill the fish without freezing it. The heat from the fish will be absorbed from the ice which then drains away in the melt water (BIM, 1999).

Cooling methods are very important to maintain the freshness and quality of fish fillets. Temperature control is very important during the whole processing time and by using brine cooling the temperature in the fish decreases about 1 to 2 °C by applying liquid cooling (Margeirsson, 2012). To be able to lower the temperature down, some cooling agents are added to the water. Salt is most commonly used, but despite their effect on lowering freezing temperature of water it also has disadvantages that involve contamination from bacterial that can results in growth of spoilage bacteria in the brine (Valtýsdóttir et al., 2010).

In precooling process, field heat of the product is removed before transport and storage to slow down the deteriorative processes that affect storage life. This is done so the product only needs minimized cooling after packaging and during storage where more focus is on maintaining low temperature. There are three types of precooling methods that can be applied, liquid cooling (LC) and slurry ice cooling (SIC) that are more widely used than the third precooling technique combined blast and contact cooling (CBC) cooler by Skaginn Ltd., Akranes, Iceland. The aim of each of these precooling methods is to lower down the temperature of fish fillets (Margeirsson, 2012). CBC cooler (also referred as "SuperChiller") freezes the skin of the fillet without excessively freezing the flesh inside and lowers the fillet core temperature no more than 1-2 °C below the initial freezing point (Tf,init) in order to minimize ice crystal growth and risk of drip (Duun, 2008). Superchilling delays bacterial spoilage, thereby increasing storage life of the product. The biggest challenge with this method is to stop the chilling/freezing at the right moment in order to get the minimum desired amount of ice (<20%) because if it goes over 30% drip will increase in the fish (Griffiths, 2012). The initial temperature of product refers to the temperature were the fist ice crystals in the fillets are formed. The initial temperature is -1 °C for most fresh food and refers to the temperature at which phase change the crystallization where water inside fish muscle is initiated (Valtýsdottir et al., 2010). The freezing point for food is normally around -2,8 °C to -0,5 °C for most food products (Table 2.2). For fish the initial freezing point depends upon fat and water content and varies between species (Valtýsdóttir, 2010). Cod has the initial freezing point of -0,9 °C according to Rahman (2009) and for salmon the initial temperature is lower due to difference in chemical composition and is assumed to be around -1,1 °C for salmon (Tommeras, 2011).

In the super-chilling process, cooling capacity is stored in the skin surface layer that makes the fish fillets able to maintain product temperature low during storage time and in distribution channels where heat load is expected. In fish muscle products, super-chilling the product resulted in better food quality in comparison to other conventional chilling methods. The shelf life of the product that is superchilled can be extended at least two up to four days depending on the conditions of the fish (Olafsdottir *et al.,* 2006).

Microbial growth limits the shelf life and quality of food products so it is important to control it to extend the shelf life. The process of super chilling is to lower the temperature of the product to 1-2 °C below the initial freezing point for each product. For most food products the refrigeration storage is between 0 °C and 4 °C , the superchilled storage -1 to -4 °C and frozen storage at -18 to -40 °C (Magnussen et al., 2008).

Table 2.2: Initial freezing point and the ratio of water content in various products (a) (Silva Sojanoviv), the initial freezing temperature for both cod and salmon fishes (b) (Tommeras, 2011) (Rahman, 2009)

(a)

Food	Water content (%)	Freezing Point (C°)
Vegetables	78-92	-0.8 to -2.8
Fruits	87-95	-0.9 to -2.7
Meat	55-70	-1.7 to -2.2
Fish	65-81	-0.6 to -2.0
Cod	79-83	-0.9
- **Salmon**	67-73	-1.1
Milk	87	-0.5
Egg	74	-0.5

(b)

Fish	Water content (%)	Freezing Point (C°)
- **Cod**	79-83	-0.9
- **Salmon**	67-73	(-1.1)

2.5.1 Super-chilling

The technology of super-chilling is a method where fraction of water is transformed into ice to protect the product from heat impacts, instead of using surrounding ice. Super-chilling improves the temperature control during processing, transportation, distribution and storage. The low temperature on the surface during super-chilling decreases the growth of microorganism that will lead to an increase in storage life. Compared to other chilling techniques super-chilling is able to increase the product yield. It is important to keep the processing time short. To be able to do that the temperature of the super-chilling medium should be kept low along with high heat transfer coefficient. Super-chilling can either be used prior to traditionally chilled distribution or be maintained throughout storage and distribution to maintain refrigeration capacity in the products. Super-chilling can also be applied in relation to fisheries in distant waters where the use of ice and/or seawater is not sufficient for maintaining the catch in a good quality (Magnussen et al., 2008). The main disadvantage of super-chilling products is the growth of ice crystals that can increase drip and break down cell structure of a food when it is prepared and during storage (Aune, 2003).

The initial freezing point is different among fish species, cod e.g. has the initial freezing point of -0,9 °C having water content of 82% (Figure 2.5). By super-chilling cod fillets down to -2 ˚C about 50-55% of the water content in the cod is frozen which results in structural damage of muscle and drip loss. In fish processing however, fish products are usually superchilled to approximately -1 ˚C to minimize the percentage of water that is frozen. In salmon the muscle with 70% of water content in the temperature range of –2 to -1,5 °C about 5-15% of the water content in the salmon fillet is frozen (Olafsdottir et al., 2012). In the super-chilling process, small ice crystals are formed that minimize the risk of structural damage and drip loss. Small ice crystals are however thermodynamically unstable which means there can be a tendency for small crystals to aggregate during warming to form larger ice crystals, this process is referred to as recrystallization (Mazur, 1984).

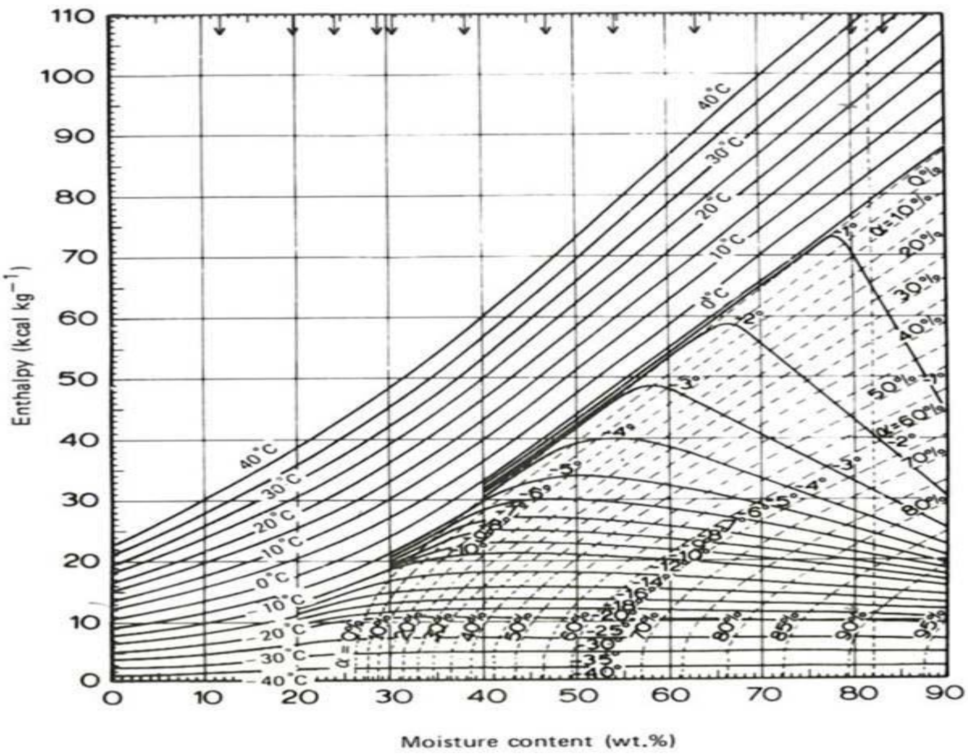


Figure 2.5: Enthalpy graph for lean fish muscle (Rha, 1975), as a function of water content and temperature. The ratio of frozen water in the muscle of the fish is given by α

2.5.2 Liquid cooling and slurry ice cooling

Fish fillets are usually immersed in either superchilled liquid (LC) or slurry ice (SIC) that lowers the initial temperature in the fish product. Cooling agents are added to the water to lower the temperature down, salt in the liquid decreases the initial freezing point of the liquid. The cooling medium is maintained at (or right above) initial freezing point of products between -1 °C and 0 °C. This makes it easier to control decrease in temperature and minimize formation of ice crystals. For CBC cooler e.g. the temperature of the equipment and environment is considerably lower which increases the risk of ice crystal growth if the process is not controlled adequately by the characteristics of the product like the thickness e.g. There can be some problems with the temperature control in the brine because it absorbs heat and the temperature will then increase with time if nothing is done. The fish is also more likely to be affected by cross-contamination due to an increase in bacteria in the liquid over the processing day (Valtýsdottir, 2011). In the liquid cooling, fillets are immersed into cooled brine (1.0-2.5% NaCl). The slurry ice cooling is similar but uses two-phase slurry ice which contains mixture of ice crystals and brine that is used for cooling medium. Studies have showed that the slurry ice cooling gives higher chilling rate than the ice does (Margeirsson, 2012). After filleting the fish fillets travel on the conveyor belt into the cooling medium where the fillets are transported on underwater conveyor belt or a turning spiral. The cooling rate depends strongly on the difference between the cooling medium and initial temperature of the product (Thompson, 2013).

Salt content of the fish may be slightly increased during immersion in brine, depending on the fish species and salt concentration of the liquid or slurry used. In Atlantic cod for example the salt content is normally around 0.2-0.3%. During liquid cooling (1.0-2.5% salinity) which takes about 6 to 15 minutes the salt content in the fish fillets will increase to 0.3-0.5% (Magnússon *et al.,* 2009).

In the brine immersion step, the fresh fish will be more sensible for microbial contamination so it is important that hygiene in the brine is good. If product is cooled very close to the product initial freezing temperature during precooling, rapid cooling like combined blast and contact cooling is necessary to ensure formation of small ice crystals within the structure of the product so muscle textural damages can be minimized (Valtýsdóttir *et al.,* 2010).

2.5.3 Combined Blast and Contact cooling

Skaginn in Akranes has been developing and designing a cooling process for few years that is called Combined Blast and Contact (CBC) cooling. CBC cooling is a method where the product goes through a freezer tunnel with temperature inside around -8 °C to -6 °C with cooling time of 6 to 10 minutes depending on the thickness and size of the fillets since fillet that are bigger and thicker require longer cooling time. Before the CBC cooling, the fish is immersed in brine that lowers the temperature in the fillets to temperature between -1 °C and 0 °C. This step is for decreasing weight loss and reduces the risk for the fillet sticking to the conveyor belt, during the CBC cooling. The fillets lay skin down on the Teflon coated aluminum belt (-35 to -40 °C) while cold air is blasted on its surface and contact cooling from below (freezing the skin) (Figure 2.6). This technology is quite efficient after 8-10 minutes inside the cooler the fillets exit having temperature in the flesh around -1 °C (Margeirsson, 2011). Before the fish fillets go through the CBC cooler, the fillets can be immersed in brine, either liquid or slurry ice cooling that lowers the initial temperature of the product (Sigurjónsdottir, 2009).

This decrease in temperature (< 0 °C) has several advantages over conventional methods by giving the fish the firmness that is needed to keep its shape during the cutting process which makes all the later processing like cutting, skinning and handling and keeping the quality of the product all the way through the processing.

Figure 2.6: Combined blast and contact cooler in the fish company Eskja

The CBC cooling is a rapid freezing process where low temperature is applied that quick-freezes the skin and surface of the fish. By quick freezing the product, small ice crystals are formed but the main proportion of muscle liquid remains unfrozen inside the fish flesh. Rapid cooling is important for the size of ice crystals however with super-chilling the size of ice crystals can easily change during storage meaning they can get bigger. The rate of heat transfer is higher in comparison to chilling where no freezing occurs in the surface of the product. Compared to other methods, CBC cooling is better due to high freezing rate since slow freezing causes big ice crystals formation that can cause damage to the product that lead to shorter storage life and increased drip loss (Bjarnason, 2012).

Proper precooling techniques before packaging result in about 3.5 days longer shelf life and freshness period compared to products were CBC cooling was not applied (no cooling and liquid cooling). In experiment done on five cod fillets during different state of cooling the liquid cooling was able to decrease the temperature from 4 °C to 2 °C in about 10 minute period. In the CBC cooler, where rapid cooling is applied the temperature decreased by approximately 3.5 °C in 7 minutes. The temperature in the fillets was then around -1 °C which was the phase where most of the changes took place. The fillets were then stored in an open box with temperature of 14 °C were the fillet temperature was stable because the cooling energy that was added to the fillet during the CBC cooler was in the form of phase change (Figure 2.7). By storing fish at 0.5 °C after CBC cooler gives shelf life of 12.5 to 14 days and if stored at -1.5 ºC in can be extended to at least shelf life of 15 days. This shelf life extension gives the fish high economic value and options in transportation like shipping the fresh fish with ship instead of air, which is more expensive (Magnusson *et al.,* 2009) (Bjarnason, 2012) (Margeirsson *et al.,* 2010).

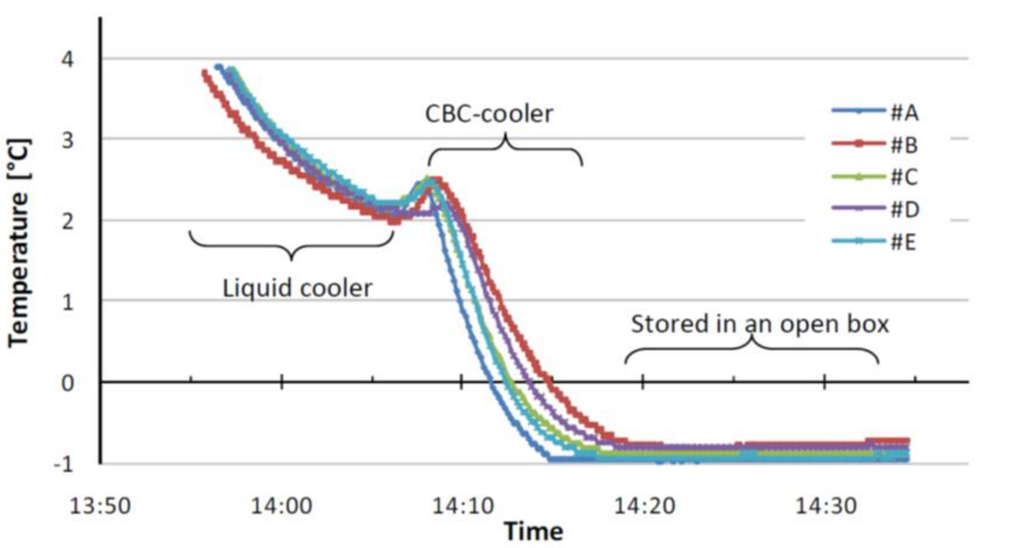


Figure 2.7: Temperature changes during different state of cooling of five different fillets as function of time (Margeirsson et al., 2011)

2.6 Quality of the cut

There are many factors that are involved when it comes to evaluating the cut itself like the condition of the material along with parameters setup in the water jet, which are crucial to obtain a good quality in the cut. Raw fish meat can soften after only one day of chilled storage.

After the fish has been caught and dead the muscle in the fish contract making the fish becoming stiff and inflexible that is described as rigor mortis. It depends on the temperature in the fish how fast the rigor mortis will occur and the faster it is the poorer the fish quality will be. Fish with high temperature will go into rigor mortis sooner than fish with lower temperature that results in gentler process. Having fish with high temperature, the rigor mortis is able to damage the delicate connective tissue between the muscles that can result in flaky fillets better known as gaping that is not adequate as a quality product (BIM, 1999). When dealing with fish muscle after catch the time and temperature are the most important factors to obtain the best quality fish product. The pH inside the fish falls after the fish dead that can also have negative affect on quality of the fish muscle such as poorer liquid holding capacity, increased gaping and rapid degradation of muscle tissue (Delbarre-Ladrat *et al.,* 2006). It also depends on the condition of the fish coming from the sea i.e. small fish spoil faster compared to large fish, and fish that have recently spawned or have been well feed will spoil faster along with oil-rich fish like salmon. Stress, exercise and activity around the time of slaughter have also been shown to have negative affect in the fish.

According to Larsen *et al.,* (2008) processing fish in pre-rigor state might increase drip loss and making it harder to remove pin bones from the fillet without damaging the flesh. There are of course some advantages by processing pre-rigor like the product could be shipped earlier, and the increase in shelf life which is very important. For salmon fillets results showed that less gaping and better color and improved texture of obtained in the salmon fillets, when processed pre-rigor.

2.7 Assessment of fish loss (kerf width)

Kerf width (Figure 2.8) is the measure of meat loss and normally reduces as the jet cuts into the meat, so that the kerf width at the lower portion is smaller than that at the upper portion of the cut.

Estimating the meat loss in worst-case scenario would be to take the maximum kerf width that is approximately equal to the nozzle diameter of 1 mm in this study. A smaller nozzle may be used to obtain a smaller kerf width, and hence less meat loss; however, because of the jet energy and abrasive size restrictions, nozzles in the vicinity of 1 mm is considered appropriate for this application. To analyse the variation of kerf width with respect to the process variables, the top kerf width, i.e. the kerf width at the jet entrance, was used because of ease of measurement (Giedra, 2013). According to Giedra. J., water jet has normally the kerf loss of 0.004” to 0.009” that will result in clean, accurate cut, no tear, and higher yield.

Generally, the top kerf width is related to the nozzle traverse speed, water pressure and salt mass flow rate. Furthermore, the top kerf width is affected by nozzle standoff distance. The meat loss can be mathematically calculated by multiplying the corresponding cross-section area. The maximum kerf width was approximately equal to the nozzle diameter, which was mostly found from the cutting of bones. In many cases, the top kerf width was much smaller than the nozzle or jet diameter, possibly because of the elastic deformation of the meat during and after the cutting process. In addition, the kerf width normally reduces as the jet cuts into the meat, so that the kerf width at the lower portion is smaller than that at the upper portion of the cutting front. Comparing to the kerf widths in traditional sawing process, abrasive water jet cutting of meat can result in reduction in meat loss, Kerf angle, or bevel, refers to the dimensional difference between the top and bottom of the cut cross-section (Wang & Shanmugam, 2009).

The transverse rate is important when it comes to kerf width like having high transverse speed the kerf width will be widest at the top and narrowest at the bottom (Figure 2.8). Having medium transverse speed the kerf width will be wider at the top than the bottom and slow transverse speed willl result in similar kerf width at the top and the bottom (figure 2.9) (Ahmet et al., 2007).

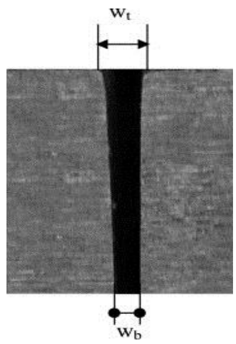


Figure 2.8: A typical side view of the kerf (W_t : top kerf width; W_b : bottom kerf width) (Hascalik et al. 2007).

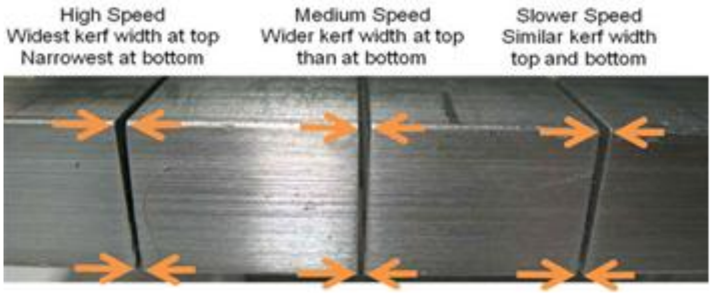


Figure 2.9: Aluminum with 3 different cut speeds (Waterjet.com, 2014)

3 Materials and methods

3.1 Materials

3.1.1 Raw material

In the experimental period from March to November 2013, cod fillets were obtained from the fish processing company Eskja hf. and the salmon (farmed) from Kalmanstjörn in Reykjanes. The cod was in most cases caught by Norðfjörð or right east of Norðfjörð. The fish was in most cases about one day old when processed.

3.1.2 Fish processing

After size grading, the fish was beheaded and filleted, and in some experiments, super-chilling and skinning was applied prior to cutting. Super-chilling involves immersion of fillets into brine mixed with ice slurry (see 2.3.1) for about 6 to 8 minutes, followed by further cooling in a CBC cooler.

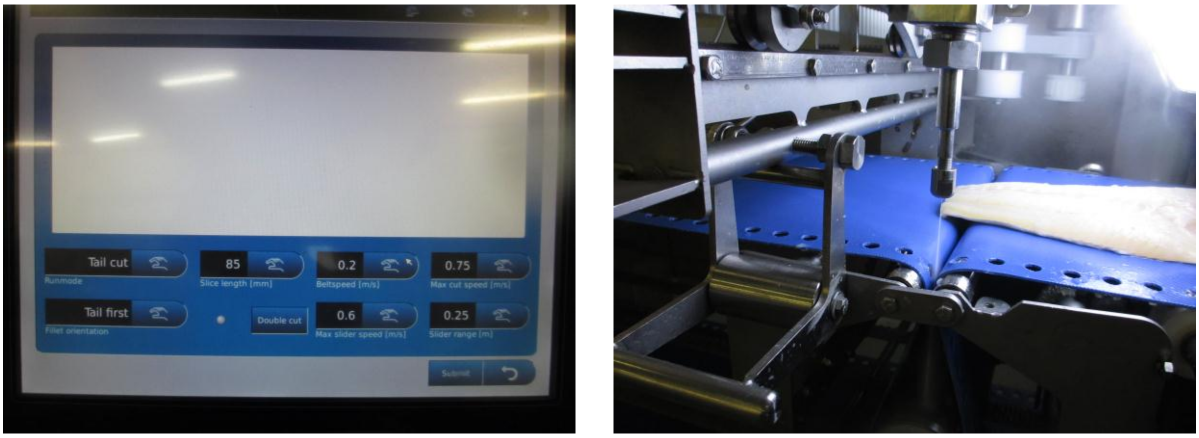
The fillet weight was approximately 50% of the total weight of the gutted fish. The cod fillets used in these experiments varied in size from 252 to 2221 grams, and salmon fillets from 828 to 1602 grams. Fillets from the same individual were usually similar in weight.

3.2 Water jet cutting, developed by Marel

The water jet system, used in the project, was the experimental version (before the prototype) manufactured and developed by Marel (Figure 3.1). The water jet pump and nozzle that were used was from KMT-Water jets. The pump is of the type Streamline SI-IV 15. It means that it has 15 hp motor with the hydraulic pump (Örnólfsson, 2012). The maximum pressure that could be applied was 3,800 bar (55,000 psi) for ultra – high - pressure water-jet cutting. The minimum outlet pressure was 345 bar (5,000 psi) and maximum outlet pressure 3,800 (55,000 psi). Diamond cutting nozzles from KMT were used that consisted of nozzle body of stainless steel and a diamond orifice. The diamond orifice is usually used when abrasive is applied, but was used in these experiments to get better particles and to prevent that particles that might come with the water could ruin the orifice diameter.

Figure 3.1: Water jet technology, that Marel was developing during the project and was used in the experimental process, the machine was a combination of x-ray detection and water jet cutting system (Marel, 2013)

The water jet system was controlled with a touch screen, where run mode, fillet orientation, slice length, max slider speed, max transverse speed and slider range were set for each experiment (Figure 3.2). The water jet pump was controlled by adjusting the pump itself. The system is such that it is possible to have the pump up to 15 meters away from the place where it is being used.



(a) (b)

Figure 3.2: Control screen for the water jet (a) water jet nozzle before trimming the tail off (b)

The cutting patterns tested in the experiments were based on testing different location in fish fillets to see how the cut is (Figure 3.3). The most common cutting pattern in fish processing is to trim the fillet, remove pin bones and post cleithrum bone and portion the fillet into loin, belly flap, middle lower and tail part (Figure 3.4). Weighting the fillets before and after the cut was done to see the drip of the fillets by cutting with water jet and to see how the yields were.

(a) (b)

Figure 3.3: Salmon fillet after portioning (a), cod fillets after portioning (b)

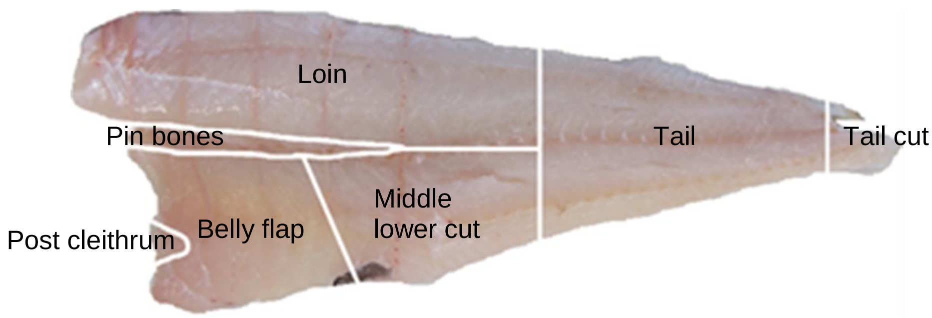


Figure 3.4: Most common fillet trimming and portioning in white fish in fish processing

3.3 Data collection

Before each experiment each fillet was marked with a number and all the information about the fillets and parameters evaluated, were written down (Table 3.1). In each experiment, fillets were weight both before and after cut to see the proportional change (%) of the fillet.

Table 3.1: Documented information about the material and quality of the cut

Fishing-date	Fishing-place	Fishing-gear	processing-day	Cooling	Skin	Orifice diameter	Orifice standoff distance	Pressure	Transverse speed	Belt speed	Cut

Fillet nr.	Size category (I, II, III, etc.)	Fillet right or left	Fillet lenght	Fillet width	Weight b. Cut	°C	Weight a. Cut	Fillet apart	Connective tissue - cut through (0-3)	Hanging together on connective tissue dorsal	Hanging together on midline	Hanging together on connective tissue ventral	Connective tissue - Bone interfere cut

Force to separate connective tissue (0-3)	Saw dust (0-3)	Muscle cut - Clean cut (0-3)	Skin cut through (0-2)	Skin - hanging together dorsal	Skin-hanging together on midline	Skin - hanging togetjher ventral	Skin - Bone interfere cut	Force to separate skin(0-3)	Skin - Clean cut(0-3)	Parts of fillet Tail cut(T), Tail portion (Tp),

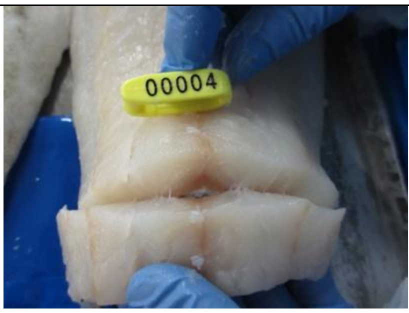
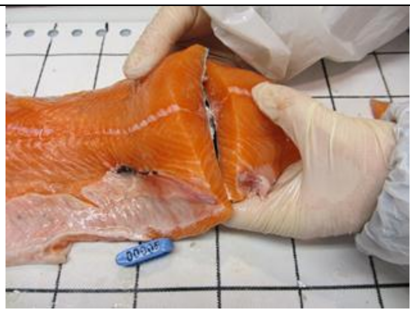
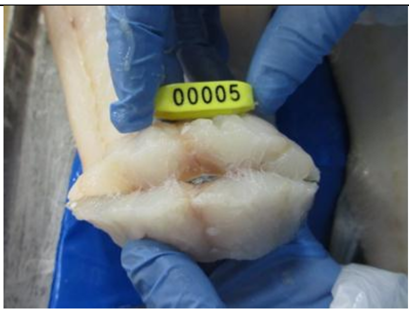
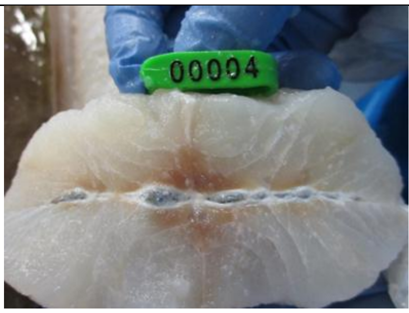
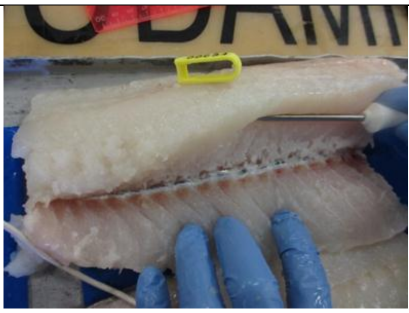
In each experiment, 3-5 fillets were used for each parameter change. The results were presented b with average and standard deviation (+/-) to show the variation between fillets. Schemes were used in evaluation of cut quality and efficiency, such as grading of the amount of saw dust, the cut of the myosepta (connective tissue), cleanness of the cut, and the cut of the skin. Grades (0-4) were given to indicate the quality of the cut, but for some of the scales grades were from 0-3 and 0-2. A grade of 0 representing the cleanness and best quality cut and by increasing the grade the quality of the cut decreased.

3.4 Schemes for evaluating quality and efficiency of the cutting

3.4.1 Saw dust

Grade of 0 represented no saw dust (saw mince), very clean cut through flesh. Grade 1 was close to a clean cut but not a perfect one since some minor saw dust was in the fillet. Grade 2 showed some saw dust in the fillets and grade of 3 represent a lot of saw dust in the fillet (Table 3.2).

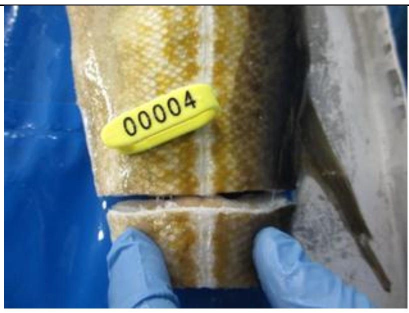
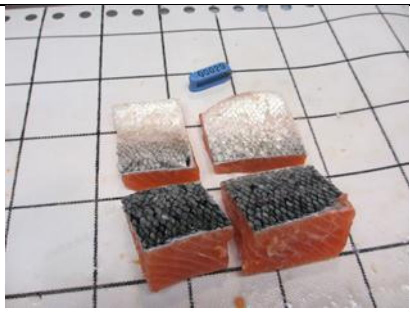
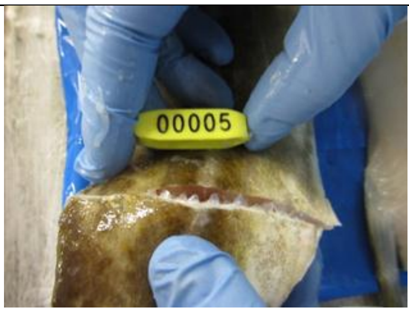
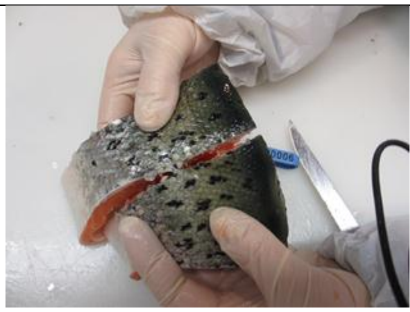
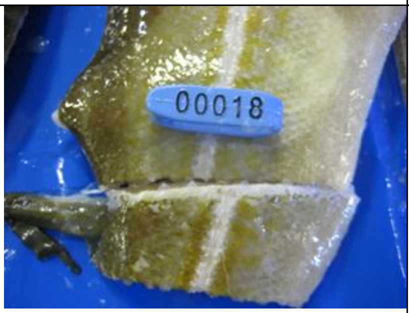
Table 3.2: Evaluation scale for saw dust in both cod and salmon fillets

Grades	Cod fillets	Salmon fillets	Evaluation Grades (0-2)
Score 0			no saw dust (saw mince),
Score 1			minor saw dust
Score 2			some saw dust
Score 3			lot of saw dust

3.4.2 Cleanness of skin cut

A grade of 0 represents a clean cut all the way through the fillet and skin. A grade of 1 showed cut through the skin where the skin might hang together at some places and some particles in the skin cut. A grade 2 shows the poorest skin cut where the water beam is not able to cut through skin and skin cut having some particles in it (Table 3.3).

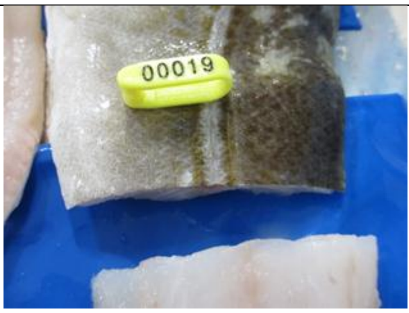
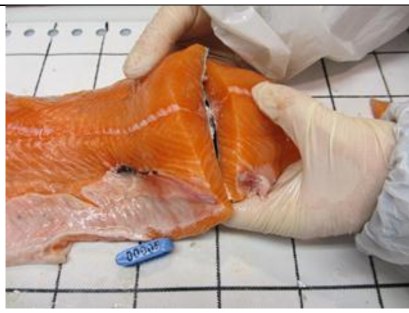
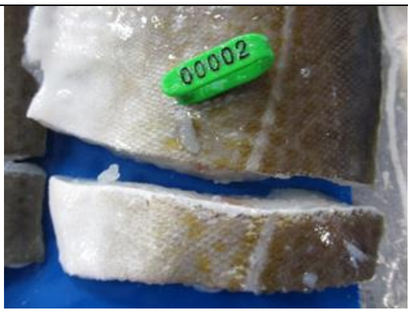
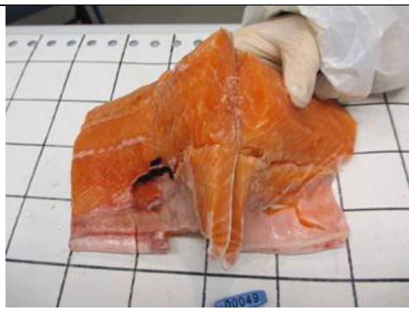
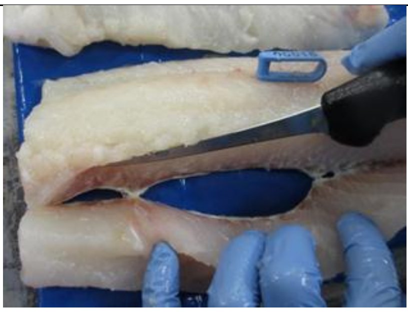
Table 3.3: Evaluation table of skin cut through both cod and salmon fillets

Grades	**Cod fillets**	**Salmon fillets**	**Evaluation Grades (0-2)**
Score 0			Goes through the skin and the cut is good
Score 1			Hanging little or nothing on the skin and having some ruined in the skin
Score 2			Hanging together on the skin and has a lot of particles in fish skin

3.4.3 Cleanness of muscle cut

A grade 0 represents very good and even cut through fillet muscle. A grade 1 shows not as clean cut with some particles in the fish. A grade 2 shows not even cut and particles are in the fillet. Grade 3 resulted in bad and uneven cut with a lot of particles and saw dust (Table 3.4)

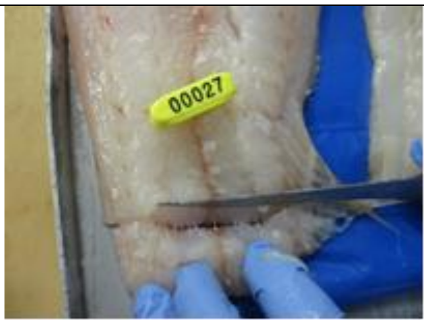
Table 3.4: Evaluation scale for cleanness of the fish muscle for both cod and salmon fillets

Grades	Cod fillets	Salmon fillets	Evaluation Grades (0-3)
Score 0			Good cut very clean and even cut
Score 1			Not has clean with a little bit of particles in the fillet
Score 2			Not even and some particles in the fillet
Score 3			Bad cut with a lot of particles and saw dust in the fillet

3.4.4 Cut through connective tissue

A grade of 0 represented complete cut through the connective tissue. A grade of 2, fillet where the fillet was hanging together in small part of the connective tissue usually on dorsal, ventral side of the horizontal septum. A grade of 3, fillet that was hanging more together and some force was needed to separate the fillet. A grade of 4, fillet was hanging together in most places in the fillet and the connective tissue is sometimes so strong, that knife is needed to separate the fillet parts (Table 3.5).

Table 3.5: Scheme used for evaluation for connective tissue of cod fillets

Grades	Cod fillets	Evaluation Grades (0-3)
Score 0		No connective tissue, fillets portions apart
Score 1		Fillet portions almost apart hanging little on ventral and dorsal side of the horizontal septum
Score 2		Hanging together in some places little force needed to separate fillet portions
Score 3		Hanging together in most places in the fillet, hard to separate the different parts

3.5 Experiments with water jet cutting

In experiment I (Table 3.6) the purpose was to see how the water jet worked and if it was possible to cut fish fillets, both cooled and superchilled with skin. In the beginning, the experiments were done at Marel and in July, 2013 the water jet was moved to the fish company, Eskja hf. where the access to raw material was better and cooling could be maintained. In experiments III to VI, cod fillets either superchilled or cooled, and with or without skin, were tested (Table 3.7). Different parameters were tested like transverse speed, water jet pressure, orifice diameter, stand-off distance. The belt speed was the only parameter that was kept almost the same, during the whole experimental process. Belt speed was normally set to 200 mm/s which was the speed of the conveyor belt that the fillet travelled after. In experiments VII and VIII, salmon fillets superchilled and cooled with skin, were tested by applying different parameters (Table 3.8).

Table 3.6: Experimental layout for testing the water jet cutting

	Material	Number of fillets	Fishing date	Transverse speed (mm/s)	Pressure (bars)	Orifice diameter size (mm)	Orifice stand-off distance (mm)	Date of trial
I	**Cod fillets, superchilled, with skin**	12	28.2.2013	--	--	0.12, 0.17	4	1.3.2013
II	**Cod fillets, cooled, with skin**	12	28.2.2013	--	--	0.12 0.17	4	1.3.2013

Table 3.7: Experimental layout for the experiments on different parameters of cod fillets

<table>
<tr><th></th><th>Material</th><th>Number of fillets</th><th>Fishing date</th><th>Transverse speed (mm/s)</th><th>Pressure (bars)</th><th>Orifice diameter size (mm)</th><th>Orifice stand-off distance (mm)</th><th>Date of trial</th></tr>
<tr><td rowspan="3">III</td><td rowspan="3">Cod fillets, superchilled, skinless</td><td>95</td><td>10.7.2013</td><td>150-900</td><td>2500</td><td>0.12</td><td>2.5, 4, 6</td><td>11.7.2013</td></tr>
<tr><td>136</td><td>9.7.2013</td><td>300-600</td><td>2500-3500</td><td>0.15, 0.17</td><td>4</td><td>10.7.2013</td></tr>
<tr><td>4</td><td>11.7.2013</td><td>300-600</td><td>2500, 3500</td><td>0.17, 0.20</td><td>4</td><td>13.7.2013</td></tr>
<tr><td rowspan="4">IV</td><td rowspan="4">Cod fillets, superchilled, with skin</td><td>16</td><td>14.7.2013</td><td>150-450</td><td>2500</td><td>0.12-0.20</td><td>4</td><td>15.7.2013</td></tr>
<tr><td>24</td><td>11.7.2013</td><td>150-750</td><td>2500-3500</td><td>0.12, 0.15</td><td>4</td><td>12.7.2013</td></tr>
<tr><td>120</td><td>8.7.2013</td><td>300-600</td><td>2000-3500</td><td>0.12, 0.17</td><td>4</td><td>9.7.2013</td></tr>
<tr><td>4</td><td>11.7.2013</td><td>300-500</td><td>2500, 3500</td><td>0.17, 0.20</td><td>4</td><td>13.7.2013</td></tr>
<tr><td rowspan="2">V</td><td rowspan="2">Cod fillets, cooled, skinless</td><td>8</td><td>14.7.2013</td><td>150-450</td><td>2500</td><td>0.12, 0.15</td><td>4</td><td>15.7.2013</td></tr>
<tr><td>40</td><td>11.7.2013</td><td>300-500</td><td>2500, 3500</td><td>0.12-0.20</td><td>4</td><td>13.7.2013</td></tr>
<tr><td rowspan="4">VI</td><td rowspan="4">Cod fillets, cooled with skin</td><td>8</td><td>14.7.2013</td><td>150-450</td><td>2500</td><td>0.12-0.20</td><td>4</td><td>15.7.2013</td></tr>
<tr><td>20</td><td>11.7.2013</td><td>300-500</td><td>2500, 3500</td><td>0.17, 0.20</td><td>4</td><td>13.7.2013</td></tr>
<tr><td>40</td><td>27.6.2013</td><td>300-600</td><td>2500, 3500</td><td>0.12-0.20</td><td>4</td><td>30.6.2013</td></tr>
<tr><td>10</td><td>27.6.2013</td><td>300-750</td><td>3500</td><td>0.12</td><td>4</td><td>28.6.2013</td></tr>
</table>

Table 3.8: Experimental layout for experiments on different parameters of salmon fillets

<table>
<tr><th></th><th>Material</th><th>Number of fillets</th><th>Fishing date</th><th>Transverse speed (mm/s)</th><th>Pressure (bars)</th><th>Orifice diameter size (mm)</th><th>Orifice stand-off distance (mm)</th><th>Date of trial</th></tr>
<tr><td rowspan="2">VII</td><td rowspan="2">Salmon fillets, superchilled, with skin</td><td>18</td><td>12.11.2013</td><td>300-600</td><td>2500, 3500</td><td>0.15</td><td>4</td><td>13.11.2013</td></tr>
<tr><td>2</td><td>11.6.2013</td><td>600</td><td>3500</td><td>0.17</td><td>4</td><td>12.6.2013</td></tr>
<tr><td rowspan="3">VIII</td><td rowspan="3">Salmon fillets, cooled, with skin</td><td>18</td><td>12.11.2013</td><td>300-600</td><td>2500, 3500</td><td>0.15</td><td>4</td><td>13.11.2013</td></tr>
<tr><td>2</td><td>11.6.2013</td><td>600</td><td>3500</td><td>0.17</td><td>4</td><td>12.6.2013</td></tr>
<tr><td>2</td><td>27.6.2013</td><td>300-750</td><td>3500</td><td>0.12</td><td>4</td><td>28.6.2013</td></tr>
</table>

3.5.1 Experiment I and II - Water jet trial

The aim of this experiment was to test 24 cod fillets with and without skin in two different cooling conditions. Twelve cod fillets from cooler with temperature from 2.3 °C to 3.4 °C and 12 superchilled fillets with temperature from -0.5 °C to -0.7 °C. The cooled and superchilled fish fillets were one day old and the fish was caught close to Olafsvik in Iceland. Two types of orifice diameters were used in this experiment 0.12 mm and 0.17 mm.

3.5.2 Experiment III – Effects of different parameters on superchilled skinless fillets

Cod fillets caught right outside Norðfjörður were used in three experiments on superchilled fillet without skin. The raw material was one day old, when the experiment was done. The experiments were done in Eskja were fillets were superchilled by using CBC cooler. Three experiments were done on 235 superchilled cod fillets without skin by applying different parameters orifice diameter (0.12, 0.15, 0.17, 0.20 mm), water jet pressure (2500, 3000, 3300, 3500 bar), transverse speed (150, 300, 400, 450, 500, 600, 750, and 900 mm/s) and orifice stand-off distance (2.5, 4, 6 cm). Temperature (core) was taken in each fillet before the water jet cut and all of the fillets were weighed before and after the cut to see the percent change in material loss after the cut. The weight range in the fillets was from 252 to 2221 grams and the temperature from 1 °C to -0,7 °C.

3.5.3 Experiment IV – Effects of different parameters on superchilled fillets with skin

The cod fillets were one day old when experiments were done. Four experiments were done on 164 superchilled cod fillets with skin in Eskja by using different parameters transverse speed (150, 300, 450, 500, 600, and 750 mm/s), water jet pressure (2000, 2500, 3000, and 3500 bar), orifice diameter (0.12, 0.15, 0.17, 0.20 mm) and having the same orifice stand-off distance 4 cm in all four experiments. The core temperature was measured in each fillet before the water jet cut and fillets were weighed before and after the cut to see how much the material loss was after the cut. The weight range for these fillets was from 703 to 1144 grams and the temperature varied from -0.8 °C to -0.2 °C.

3.5.4 Experiment V – Effects of different parameters on cooled cod fillets without skin

Two experiments were done on cooled filets without skin. Cod (n=48) fillets that were one day old were tested in Eskja. The fillets were weighted before and after the water jet cut and core temperature taken. The purpose was to see the difference between fillets by applying different parameters transverse speed (150, 300, 400, 500 mm/s), water jet pressure (2500, 3000, 3500 bar), orifice diameter (0.12, 0.15, 0.17, 0.20 mm), and by having the same orifice stand-off distance 4 cm during both experiments. For the cooled fillets without skin the weight range was from 661 to 1049 grams and the temperature varied from 4,2 °C to 2,1 °C.

3.5.5 Experiment VI - Effects of different parameters on cooled cod fillets with skin

Four experiments on cooled cod fillets were done in Eskja. Fillets were measured before and after cut and core temperature taken. The fillets were one day old when experiments were done. Cod (n=78) fillets were tested by applying different parameters transverse speed (300, 450, 500, 600, 750 mm/s), water jet pressure (2500, 3000, 3500 bar), orifice diameter (0.12, 0.15, 0.17, 0.20 mm), and having the same orifice stand-off distance 4 cm during these four experiments.

3.5.6 Experiment VII - Effects of different parameters on superchilled salmon fillets with skin

The raw material was one day old caught at Kalmanstjörn in Reykjanes. The gutted fishes were marked with a marker indicating a number and color to make the work more organized and easier. The length, height and the weight was measured. The fish was then gutted and filleted. Right and left fillet from the same fish was marked to have the paired comparison of the cooled and superchilled fillets by using the same fish. The fillets were then placed in the cooler covered in ice over the night. The fillets for the super-chilling were taken to Eskja for the combined blast and contact cooler (CBC) cooler. First the fillets were placed in immersing brine for couple of minutes and then put two times through the CBC cooler. The fillets were then covered in ice and placed in the freezer in Marel until the experiment started. Fillets were measured before and after the cut and temperature was also taken.

The salmon was one day old caught in Kalmanstjörn (Reykjanes). Two experiments were done on 20 superchilled salmon fillets, testing different parameters: transverse speed (300, 400, 500, 600 mm/s), water jet pressure (2500 and 3500 bar), orifice diameter (0.15, and 0.17 mm), and having the same orifice stand-off distance 4 cm during these two experiments. The core temperature for superchilled fillets was around from -1.2 °C to -0.6 °C and weight range from 828 to 1602 grams.

3.5.7 Experiment VIII – Effects of different parameters on cooled salmon fillets with skin

Three experiments were done on cooled salmon fillets with skin in Marel. Different parameters were used transverse speed (200, 400, 500, 600, 750 mm/s), water jet pressure (2500 and 3500 bar), orifice diameter (0.12, 0.15, 0.20 mm), and having the same orifice stand-off distance 4 cm during the whole experiment.

3.6 Evaluation of processing yields and duration of manual trimming and portioning

In experiment IX (Table 3.9), the processing yield was evaluated by using trimming and portioning. Superchilled cod fillets were used with the weight range of 262 to 1560 grams in average 787 grams and average length of 54 cm and width of 18 cm. The core temperature in the cod fillets was in average -0.6 °C.

Table 3.9: Experimental layout in evaluation of processing yield of superchilled skinless cod fillet, after manual trimming and portioning

	Material	Number of fillets	Fishing date	Transverse speed (mm/s)	Pressure (bars)	Orifice diameter size (mm)	Orifice stand-off distance (mm)	Date of trial
IX	Cod fillet, superchilled, skinless	50	18.11.2013	--	--	--	--	9.11.2013
X		16	27.11.2013	--	--	--	--	28.11.2013

3.6.1 Fillet portioning and trimming of processing

In both of these experiments (IX and X), the purpose was to use manual trimming and portioning to see how much each portion of the fillets weighted. The experiments were done in Eskja hf. where skilled employer from trimming line was used to trim 50 fillets (experiment IX) and employer from Marel was used to trim 16 fillets (experiment X). This was done to see the comparison between the weight of each portion in the fillets by using employer that works fast and cut as closest to the pin bones as possible. Each portion of the fillet was weighed after each cut. The fillets trimming and portioning included: part with pin bones, tail trimming, loin, belly flap, tail portion and some trimming needed to remove defects, resulting from in proper handling or filleting (debris, loin bone, rib, blood, fin bone, back spine). The purpose of this experiment was also to time couple of the trimming employers at Eskja to see how long time it takes to trim and portion one fillet.

3.6.2 Time of fish processing and measurements of temperature

The purpose of this experiment was to evaluate processing time in Eskja and see how long time it took fish to go through the fish processing by measuring the time from the beginning of beheading until the fish has gone through skinning. The temperature was taken in the fillet after the immersing brine and after the CBC cooler.

3.7 Data analysis

In the experiments the main goal was to see if the water beam was able to cut through the fillet or not. For each experiment, information about raw material and grades for cutting efficiency and quality that were used in each experiment were documented in Excel and average of weight before and after the cut calculated to see the proportional change in material after the cut. The average value for weight, size (length and width), and temperature and average value of each fillet part were calculated. Minimum and maximum values were also calculated along with standard deviation. Statistical comparison was done on the parameters used in the experimental process by using Anova and Duncan tests to see the variation between different parameters and which parameter had the strongest effects in each experiment.

For the water jet setup different parameters were tested to see where the water beam was getting through the fillet. The parameters were compared using Anova and Duncan test to see the comparison between different transverse speed, water jet pressure, orifice diameter and stand-off distance.

4 Experimental design

The main objective was to study the relationship between water jet cutting conditions, fish physical properties and temperature of the fish fillets, in water jet cutting of cod and salmon fillets. The main criteria for success were the cutting efficiency and quality of cut. The purpose was to gather information on optimum running conditions, which were used in designing FleXicut. Flexicut is a system for bone detection by x-rays and removal of pin bones with water jet cutting.

Different types of parameters were applied between each and every experiment. Five different cutting patterns were applied and fillet portioning into: tail trimming, tail portion, loin, pin bone removal and belly flap. The specific experimental design is given in Table 3.1, involving six levels of nozzle transverse speed, four levels of pressure, four levels of orifice size and three levels of stand-off distance of the orifice. The fillets were either cooled around 2 °C or superchilled around -1° C (Table 4.1).

Table 4.1: Parameters used in the experimental period

Raw material	Water jet setup
Species • Cod • Salmon	**Transverse speed** • 150, 300, 400, 450, 500, 600, 750, and 900 mm/s
Processing • Skin • Skinless	**Orifice diameter size** • 0.12, 0.15, 0.17, and 0.20 mm
Cutting location on fillet • Area around pin bones • Loin • Belly flap • Tail	**Water jet pressure** • 2000, 2500, 3000, 3300, and 3500 bar
Pre-treatment • Superchilled • Cooled	**Orifice stand-off distance** • 2.5, 4, and 6 cm
	Belt speed • 250 mm/s (constant)

Experiments on processing time and utilization of fish fillets were done to see the benefits of changing from manual to water jet cutting. The experiments were limited due to quantity and employees and the variability of the raw material was not taken into account.

In the beginning of the experimental process a simple experiment was done to see how the water jet worked and to decide at which range the parameters worked. It was then decided to develop an evaluation scale that would be used for the other experiments. Before each experiment core temperature in the fillets was measured and fillets were placed on conveyor belt with 5x5 cm boxes that would be used to measure length and width of the fillets from a picture that was taken of each fillet during the process (Figure 4.1). Fillets were also weighted before and after water jet cutting to see how much the loss in material was. Parameters evaluated for were quality of the cut, saw dust in the fillet, cleanness of the cut, cleanness of the skin cut, and how strong the connective tissue is and the force it takes to separate the connective tissue (Table 4.2).

Table 4.2: Parameters for evaluation of fillets prior and after water jet cutting

Pre water jet cut	**After water jet cut**
• Weight of fish and fillet • Temperature • Width and length (of fish) fillet	• Weight of the fillet portions • Cutting efficiency • Quality of cut edge

Figure 4.1: Fillet lead down on conveyor belt to measure length and width

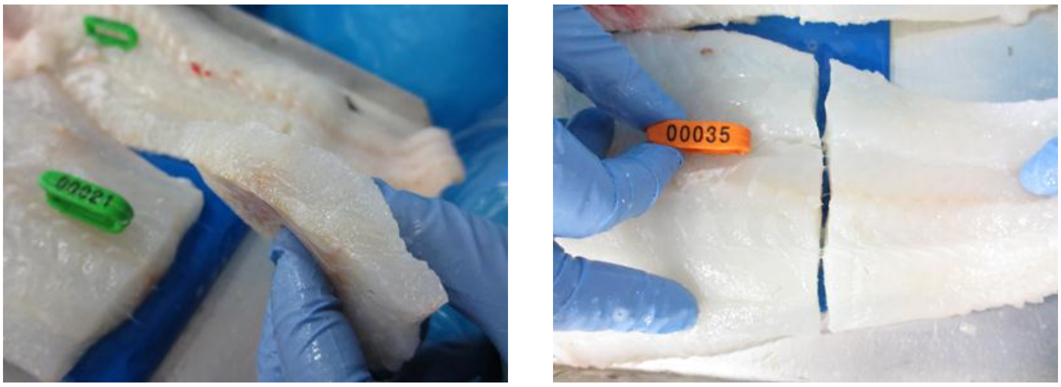
5 Results

5.1 Water jet testing

The water jet was working well during the experiment and getting through fillets in most of the cases, but was not able to cut through bone. Experiment I and II showed that water jet cutting was working well for both the cooled and superchilled cod fillets. The cut was getting through both the superchilled and the cooled fillets, but superchilled fillets were firmer that resulted in better and cleaner cut.

5.2 Experiment III – Superchilled skinless cod fillets

Experiment III showed that the water jet cut was cutting well through superchilled cod fillets without skin. There were in some cases some saw dust in the fillets especially when transverse speed was increased to 600 mm/s (Table 5.2). The cut was clean, when applying transverse speed in the range from 150 to 600 mm/s (Figure 5.1a). The cutting efficiency was high when cutting with transverse speed of 150 and 300 mm/s compared to higher transverse speeds. The water jet was able to cut at a pressure 2000 bar, but pressure of 3500 bar resulted in cleaner muscle cut, less saw dust and connective tissue compared to pressure from 2000 to 3000 bar (Table 5.1). More noise came from the water jet when higher pressure was used. Orifice diameters of 0.12 and 0.15 mm resulted in a cleaner cut and less saw dust compared to orifice diameters of 0.17 and 0.20 mm. The orifice stand-off distance did not have great impact so in later experiments standoff distance of 4 cm was usually applied (Table 5.3). The fillet was hanging together on connective in some part of the fillets especially in the tail portion and in most cases on the ventral and dorsal side of the horizontal septum (Figure 5.1b). The water beam was not able to cut through bones, which means that the fillet was not separated because of the bone.



(a) (b)

Figure 5.1: Cut clean and getting through fillet (a), the connective tissue was the biggest issue in the tail portion (b)

The result did vary because of variation in size and fish temperature. For most cases the grade increased with increasing transverse speed. The saw dust in the fillets was more likely to increase having orifice diameter of 0.17 mm compared to orifice diameter of 0.12 mm.

Table 5.1: Average evaluation grades for cod fillets with different parameters (standard deviation (+/-))

Parameters			**Evaluation grades (average of five fillets)**				**Part of the fillet**
Pressure (bar)	Orifice diameter (mm)	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Tail portion, Tail cut, Middle, Belly flap, Loin
3500	0.12	300	1 (+/-1)	0	0	0	Tail portion (about 100 gram piece)
		450	1 (+/-1)	0	0	0	
		600	1 (+/-1)	1 (+/-1)	0	0	
3000	0.12	300	0	0	0	0	
		450	1 (+/-1)	1 (+/-1)	0	0	
		600	1 (+/-1)	1 (+/-1)	1	0	
2500	0.12	300	1 (+/-1)	1 (+/-1)	0	0	
		450	1 (+/-1)	1 (+/-1)	1	1	
		600	1 (+/-1)	1	1	1 (+/- 1)	
2000	0.12	300	1 (+/-1)	1 (+/-1)	0	1	
		450	1 (+/-1)	1 (+/-1)	1	1	
		600	1 (+/-1)	1 (+/-1)	1	1 (+/-1)	
3500	0.17	300	0	0	0	0	
		450	0	0	1	0	
		600	0	0	1	0	
3000	0.17	300	1 (+/-1)	0	1 (+/-1)	0	
		450	0	0	1 (+/-1)	0	
		600	1 (+/-1)	0	1 (+/-1)	1(+/-1)	
2500	0.17	300	1 (+/-1)	1 (+/-1)	1 (+/-1)	1 (+/-1)	
		450	1 (+/-1)	1 (+/-1)	1	0	
		600	1 (+/-1)	1 (+/-1)	1	1 (+/-1)	
2000	0.17	300	1 (+/-1)	1 (+/-1)	1 (+/-1)	1 (+/-1)	
		450	1 (+/-1)	2 (+/-1)	2 (+/-1)	1 (+/-1)	
		600	2 (+/-1)	2	2 (+/-1)	2 (+/-1)	

Table 5.2: Evaluation table with different pressure, orifice diameter and transverse speed (Standard deviation (+/-))

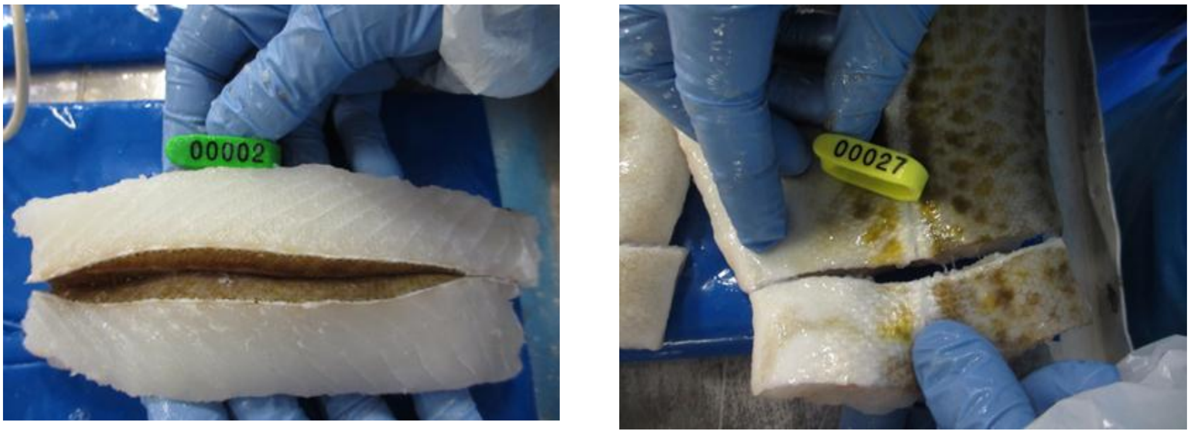
Parameters			**Evaluation grades (average of five fillets)**				**Part of the fillet**
Pressure (bar)	Orifice diameter (mm)	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Tail portion, Tail trimming, Middle, Belly flap, Loin
3500	0.15	300	1	1	0	0	Tail portion (about 100 gram piece)
		450	1	1	1	0	
		600	2 (+/-1)	2	1	1	
3000		300	1 (+/-1)	1 (+/-1)	0	0	
		450	1 (+/-1)	1 (+/-1)	1	1 (+/-1)	
		600	2 (+/-1)	2 (+/-1)	2 (+/-1)	2 (+/-1)	
2500		300	2 (+/-1)	2 (+/-1)	0	0	
		450	1	1	1	1	
		600	1	1	1 (+/-1)	1 (+/-1)	
2000		300	1 (+/-1)	2 (+/-1)	1	1	
		450	2 (+/-1)	2 (+/-1)	1 (+/-1)	2	
		600	2 (+/-1)	2 (+/-1)	2	2	
3500	0.12	300	0	0	0	0	
		450	1 (+/-1)	1 (+/-1)	1	0	
		600	2 (+/-1)	2 (+/-1)	1 (+/-1)	0	
3000		300	0	0	1	1	
		450	1	1	1 (+/-)	1 (+/-1)	
		600	1	1	1 (+/-1)	1 (+/-1)	
2500		300	1 (+/-1)	1 (+/-1)	1	1 (+/-1)	
		450	2	2	1	1	
		600	1 (+/-1)	1 (+/-1)	1 (+/-1)	1 (+/-1)	
2000		300	1 (+/-1)	1 (+/-1)	1 (+/-1)	1 (+/-1)	
		450	1 (+/-1)	1 (+/-1)	1 (+/-1)	1 (+/-1)	
		600	2	2	1 (+/-1)	2	

Table 5.3: Evaluation grades for average of five cod fillets (standard deviation (+/-))

Parameters				**Evaluation grades (average of five fillets)**				**Part of the fillet**
Pressure (bar)	Orifice diameter (mm)	Height of orifice diameter (cm)	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Tail portion, Tail trimming, Middle, Belly flap, Loin
2500	0.12	4	300	0	0	1	0	Tail portion
			300	0	0	0	0	Belly flap
			450	1	0	1	0	Tail portion
			450	0	0	0	0	Tail trimming
			450	0	0	0	0	Belly flap
			600	2(+/-1)	2(+/-1)	2(+/-1)	2(+/-1)	Tail portion
			600	1(+/-1)	1(+/-1)	0	0	Tail trimming
			600	1	0	0	0	Belly flap
			750	1(+/-1)	1(+/-1)	1(+/-1)	1(+/-1)	Tail portion
			750	1	1	2	2 (+/-1)	Belly flap
		2.5	300	1	0	1(+/-1)	1(+/-1)	Tail portion
			300	1	0	2	2	Belly flap
			450	1	0	1	2	Tail portion
			450	1	1	1	1	Tail trimming
			450	0	0	1	2	Belly flap
			600	1(+/-1)	1	1	2(+/-1)	Tail portion
			600	1(+/-1)	2(+/-1)	1	1(+/-1)	Tail trimming
			600	0	0	2(+/-1)	2(+/-1)	Belly flap
			750	1	1(+/-1)	2	1(+/-1)	Tail portion
			750	1	0	2	2	Belly flap
		6	300	0	0	0	0	Tail portion
			300	0	0	1	1	Belly flap
			450	1	0	0	0	Tail portion
			450	1(+/-1)	1(+/-1)	1	1	Tail trimming
			450	0	0	1	1	Belly flap
			600	1(+/-1)	1(+/-1)	0	1	Tail portion
			600	1	1	1(+/1)	1(+/-1)	Tail trimming
			600	0	0	1	1	Belly flap
			750	2(+/-1)	1(+/-1)	1	1(+/-1)	Tail portion
			750	0	0	1	1	Belly flap
			750	0	0	1	1	Belly flap

5.3 Experiment IV – Superchilled cod fillets with skin

In experiment IV superchilled fillets with skin were tested. Results showed that the cut was getting through the skin and was good in most cases but not if the water beam ended on bones Figure (5.2a). The skin cut was clean when cutting with transverse speeds from 150 to 600 mm/s. If the transverse speed was increased over 600 mm/s resulted in particles in the skin and uneven cut. The connective tissue was the main problem, where the cut was in some cases getting through the skin but the portions hanging together on the connective tissue (Figure 5.2b). Orifice diameter of 0.12 and 0.15 mm resulted in cleaner cut and less saw dust compared to orifice diameter of 0.17 and 0.20 mm. The water jet pressure was getting through with pressure of 2000 bar, but the jet through the fillet was cleanest between water jet pressure of 2500 and 3500 bar.



(a) (b)

Figure 5.2: Cut getting through skin but hanging together on the connective tissue (a), clean muscle cut when applying transverse rate of 300 mm/s (b)

Four fillets were used for each parameter change during the experiment. The average of 4 fillets of each evaluation grade was calculated and standard deviation shown. The water jet cut was getting better through fillets when lower transverse speed was used. Transverse speed of 150 mm/s resulted in clean cut and no saw dust for most of the fillets. Transvers speed higher than 600 mm/s resulted in a lot of saw dust especially in the loin part of the fillets (Table 5.4a). For the belly flap the cut was getting through fillet parts at higher transverse speed and the cut was cleaner and less saw dust in the fillet compared to the loin and tail part (Table 5.4b). The connective tissue in the tail portion was the biggest problem where the fillet was hanging together. The saw dust, cleanness of muscle cut, cut through connective tissue and force to separate the connective tissue increased when transverse speed of 750 mm/s was used. The grades were higher when cutting through the tail portion and loin compared to belly flap. The orifice diameter of 0.17 and 0.20 resulted in increase in saw dust and decrease in cutting efficieny (Table 5.5a,b).

Table 5.4: Average and standard deviation of evaluation grades for cod fillets with different orifice diameter 0.12 mm (a) and 0.15 mm (b) and transverse speed (standard deviation (+/-))

(a)

Parameters				**Evaluation grades (average of four fillets)**						**Part of the fillet**
Pressure (bar)	Orifice diameter (mm)	Height of orifice diameter (cm)	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Skin cut through fillet	Cleanness of skin cut	Tail portion, Tail trimming, Middle, Belly flap, Loin
2500	0.12	6	150	0	0	0	0	0	0	Tail portion
			150	0	0	0	0	0	0	Belly flap
			450	2(+/-1)	2(+/-1)	1	2(+/-1)	2	1(+/-1)	Tail portion
			450	0	0	0	0	0	0	Belly flap
			450	0	0	2(+/-1)	1(+/-1)	1	0	Loin
			750	3	3	2	2	3	0	Tail portion
			750	0	0	0	1(+/-1)	1(+/-1)	0	Belly flap
			150	0	0	0	0	0	0	Tail portion
			450	1(+/-1)	1	1(+/-1)	1(+/-1)	1(+/-1)	0	Tail portion
			750	1	2(+/-1)	1	1 (+/-1)	2	0	Tail portion
3000			150	0	0	0	0	1(+/-1)	0	Tail portion
			150	0	0	0	0	0	0	Belly flap
			450	1(+/-1)	1(+/-1)	1(+/-1)	1	1(+/-1)	1	Tail portion
			450	0	0	0	0	0	0	Belly flap
			450	0	0	2(+/-1)	2(+/-1)	1(+/-1)	0	Loin
			750	1(+/-1)	1(+/-1)	2(+/-1)	2(+/-1)	2(+/-1)	2(+/-1)	Tail portion
			750	0	0	2(+/-1)	1(+/-1)	2(+/-1)	0	Belly flap
			150	0	0	0	0	0	0	Tail portion
			450	0	0	0	0	0	1	Tail portion
			750	1(+/-1)	1(+/-1)	1	1(+/-1)	0	1	Tail portion
3500			150	0	0	1(+/-1)	1	0	1	Tail portion
			150	0	0	0	0	0	0	Belly flap
			450	0	0	1(+/-1)	1(+/-1)	0	1	Tail portion
			450	0	0	1(+/-1)	0	0	0	Belly flap
			450	0	0	2(+/-1)	2(+/-1)	1	1(+/-1)	Loin
			750	1	1	2	1(+/-1)	0	1	Tail portion
			750	0	0	3	1(+/-1)	0	1(+/-1)	Belly flap

(b)

Parameters				Evaluation grades (average of four fillets)						Part of the fillet
Pressure (bar)	Orifice diameter (mm)	Height of orifice diameter (cm)	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Skin cut through fillet	Cleanness of skin cut	Tail portion, Tail trimming, Middle, Belly flap, Loin
3300	0.15	6	150	0	0	0	0	0	0	Tail portion
			150	0	0	0	0	0	0	Belly flap
			450	1(+/-1)	1	1	1	2	0	Tail portion
			450	0	0	0	0	0	0	Belly flap
			450	0	0	1(+/-1)	(+/-1)	1 (+/-1)	0	Loin
			750	3	3	2	2	3	0	Tail portion
			750	0	0	0	1(+/-1)	1(+/-1)	0	Belly flap
			150	0	0	0	0	0	0	Tail portion
			450	1(+/-1)	1	0	1(+/-1)	1(+/-1)	0	Tail portion
			750	1	0	0	0	2	0	Tail portion
2500			150	0	0	0	0	1(+/-1)	0	Tail portion
			150	0	0	0	0	0	0	Belly flap
			450	1(+/-1)	1(+/-1)	1(+/-1)	1	1(+/-1)	1	Tail portion
			450	0	0	0	0	0	0	Belly flap
			450	0	0	2(+/-1)	1	1(+/-1)	0	Loin
			750	1(+/-1)	1(+/-1)	2(+/-1)	2(+/-1)	2(+/-1)	2(+/-1)	Tail portion
			750	0	0	2(+/-1)	1(+/-1)	2(+/-1)	0	Belly flap
			150	0	0	0	0	0	0	Tail portion
			450	0	0	0	0	0	1	Tail portion
			750	1(+/-1)	1(+/-1)	1	1(+/-1)	0	1	Tail portion
3000			150	0	0	1(+/-1)	1	0	1	Tail portion
			150	0	0	0	0	0	0	Belly flap
			450	0	0	1(+/-1)	1(+/-1)	0	1	Tail portion
			450	0	0	1(+/-1)	0	0	0	Belly flap
			450	0	0	2(+/-1)	2(+/-1)	1	0	Loin
			750	1	1	2	1(+/-1)	0	1	Tail portion
			750	0	0	3	1(+/-1)	0	0(+/-1)	Belly flap

Table 5.5: Evaluation grades for superchilled cod fillets with skin with different transverse speed and orifice diameter 0.12, 0.15, 0.17 mm (a) and 0.20 mm (b) (standard deviation (+/-))

(a)

Parameters				**Evaluation grades (average of five fillets)**							**Part of the fillet**
Orifice diameter (mm)	Cooling	Skin	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Skin cut through fillet	Force to separate skin	Cleanness of skin cut	Tail portion, Tail trimming, Middle, Belly flap, Loin
0.12	Super chilled	With skin	150	0	0	0	0	0	0	0	Tail portion
			150	0	0	1	1	0	0	1	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	0	0	0	0	0	0	0	Tail portion
			300	1(+/-1)	1(+/-1)	1	1	0	0	0	Middle
			300	0	0	0	0	0	0	0	Belly flap
			300	0	0	1	1(+/-1)	1(+/-1)	1(+/-1)	1(+/-1)	Loin
			450	0	0	1	1	0	1	1	Tail portion
			450	0	0	1	1	0	1	1	Middle
			450	0	0	1(+/-1)	1(+/-1)	1	0	0	Belly flap
0.15			150	0	0	0	0	0	0	0	Tail portion
			150	0	0	0	0	0	0	0	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	0	0	0	0	0	0	0	Tail portion
			300	1	1	0	1	0	0	0	Middle
			300	0	0	1(+/-1)	0	0	1(+/-1)	1	Belly flap
			450	1(+/-1)	1(+/-1)	0	0	1(+/-1)	1(+/-1)	0	Tail portion
			450	1	0	1	0	0	1	0	Middle
			450	0	0	1(+/-1)	1(+/-1)	0	0	0	Belly flap
			150	0	0	0	0	0	0	0	Tail portion
			150	0	0	1	1	0	0	0	Middle
0.17			150	0	0	0	0	0	0	0	Tail portion
			150	0	0	1	1	0	1	0	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	0	1	0	1	1	0	0	Tail portion
			300	0	0	1(+/-1)	1(+/-1)	2	2	0	Middle
			300	0	0	1	0	1	0	0	Belly flap
			300	0	0	2(+/-)	1(+/-1)	1	1	1	Loin
			450	1(+/-1)	1(+/-1)	1(+/-1)	1(+/-1)	0	0	0	Tail portion
			450	1(+/-1)	1(+/-1)	2	2	0	2	2	Middle
			450	0	0	1(+/-1)	1(+/-1)	0	0	0	Belly flap

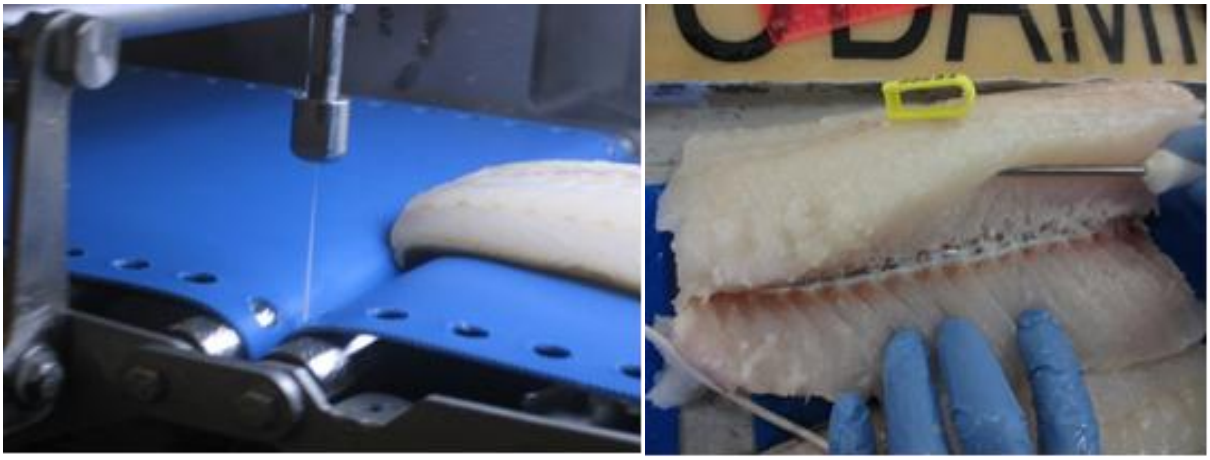
(b)

Parameters				Evaluation grades (average of five fillets)							Part of the fillet
Orifice diameter (mm)	Cooling	Skin	Speed (mm/s)	Cut through connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Skin cut through fillet	Force to separate skin	Cleanness of skin cut	Tail portion, Tail trimming, Middle, Belly flap, Loin
0.20	Super chilled	With skin	150	1(+/-1)	0	0	0	0	0	1	Tail portion
			150	1(+/-1)	1	1	1	0	0	1	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	1(+/-1)	0	1	1	1	0	1	Tail portion
			300	1(+/-1)	1	1(+/-1)	1	1	0	1	Middle
			300	0	0	0	0	1 (+/-1)	0	0	Belly flap
			300	1(+/-)	1	2	1(+/-1)	1	0	1	Loin
			450	1(+/-1)	1	2(+/-1)	1	1	0	1	Tail portion
			450	1(+/-1)	1	2(+/-1)	2(+/-1)	1	1	2	Middle
			450	0	0	1	1	1	1	1	Belly flap

5.4 Experiment V and VI – Cooled cod fillets with and without skin

The results showed that the water jet cut was getting through the fillets. For some of the fillets the temperature in the fillet was too high (>4 ˚C) that made the cut more difficult, since the muscle was not as firm (was softer). In some cases the tail portion was too soft making the tail going into the gap on the conveyor belt (Figure 5.3a). Orifice diameters of 0.12 and 0.15 mm resulted in better cut compared to 0.17 and 0.20 mm. The water jet transverse speed of 150 mm/s was getting through the fish fillet in most cases. Increasing cutting speed resulted in more saw dust in the fillet (Figure 5.3b). The water jet pressure did not have great impact but in some cases water jet pressure of 3500 bar resulted in better quality and cleaner cut.

Evaluation grades were used to evaluate the quality of the cut for both cooled cod fillets with and without skin. The results showed that the fillet was hanging more together on connective tissue when higher transverse speed was used (450 mm/s). Lower transverse speed resulted in better cut and less saw dust. The jet was getting better through skin when lower transverse speed was used (150 and 300 mm/s) compared to transverse speed of 450 mm/s. The jet was getting though belly flap in almost all cases and the cut was clean and little or no saw dust in that part of the fillet (Table 5.6).



(a) (b)

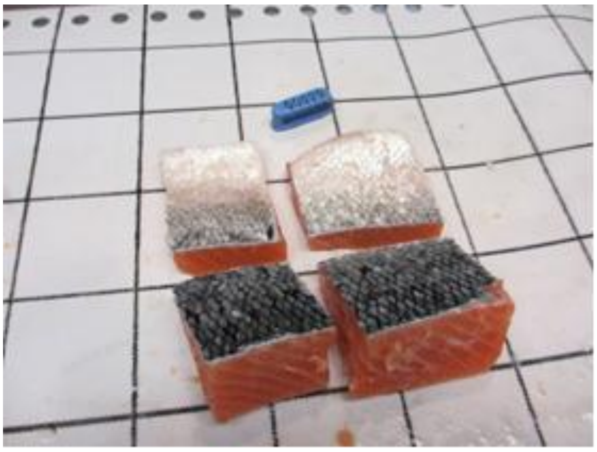
Figure 5.3: Tail portion of cooled fillet going into the gap (a), saw dust in cooled fillets by applying increased transverse speed (b)

Table 5.6: Evaluation grades for cod fillets with and without skin with different transverse speed and orifice diameter (standard deviation (+/-))

Parameters				**Evaluation grades (average of five fillets)**							**Part of the fillet**
Orifice diameter (mm)	Cooling	Skin	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Skin cut through fillet	Force to separate skin	Cleanness of skin cut	Tail portion, Tail trimming, Middle, Belly flap, Loin
0.12	Cooled	Without skin	150	0	0	0	0	--	--	--	Tail portion
			150	0	0	0	0	--	--	--	Middle
			150	0	0	0	0	--	--	--	Belly flap
			300	1(+/-1)	1(+/-1)	0	0	--	--	--	Tail portion
			300	1	1	0	1	--	--	--	Middle
			300	0	0	0	0	--	--	--	Belly flap
			300	0	0	2(+/-1)	2	-	--	--	Loin
			450	1	1	0	1	-	--	--	Tail portion
			450	1(+/-1)	1(+/-1)	1	1	--	--	--	Middle
			450	0	0	1	1				Belly flap
		With skin	150	0	0	0	0	0	0	0	Tail portion
			150	1	1	0	1	0	0	0	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	1	1	0	0	0	0	0	Tail portion
			300	1(+/-1)	1(+/-1)	1	1(+/-1)	1	1	0	Middle
			300	0	0	0	0	0	0	0	Belly flap
			300	0	0	2	1(+/-1)	1	1	1	Loin
			450	2	2	0	1(+/-1)	0	2	1(+/-1)	Tail portion
			450	1(+/-1)	1(+/-1)	1	1(+/-1)	1	1	0	Middle
			450	0	0	1(+/-1)	2(+/-1)	1	0	0	Belly flap
			450	0	0	2	2	2(+/-1)	2(+/-1)	1	Loin
0.15		Without skin	150	0	0	0	0				Tail portion
			150	0	0	0	0				Middle
			150	0	0	0	0				Belly flap
			300	0	0	0	0				Tail portion
			300	0	0	1(+/-1)	1(+/-1)				Middle
			300	0	0	0	0				Belly flap
			300	0	0	1(+/-1)	1(+/-1)				Loin
			450	1(+/-1)	1(+/-1)	0	0				Tail portion
			450	1(+/-1)	1(+/-1)	1	1				Middle
			450	0	0	2(+/-1)	1				Belly flap
		With skin	150	0	0	0	0	1	0	0	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	1(+/-1)	1(+/-1)	0	0	0	0	0	Tail portion
			300	1(+/-1)	1(+/-1)	1(+/-1)	0	1	1	0	Middle
			300	0	0	0	0	0	0	0	Belly flap
			300	1(+/-1)	1(+/-1)	2(+/-1)	2(+/-1)	2	1	1	Loin
			450	2(+/-1)	2(+/-1)	1(+/-1)	1	1(+/-1)	0	1	Tail portion
			450	2	2	1(+/-1)	1	1(+/-1)	1	1	Middle
			450	0	0	0	1(+/-1)	0	0	0	Belly flap

5.5 Experiment VII – Superchilled salmon fillets with skin

The results showed that the water jet was able to cut salmon fillets. Cut through skin was very good and the cut was usually getting through the fillet (Figure 5.4a). The saw dust in the fillets increased with higher transverse rate (600 mm/s) (Figure 5.4b). The water jet pressure was in some cases getting better through at water jet pressure of 3500 bar. Orifice diameter of 0.15 mm did results in better quality of the cut compared to 0.17 mm.



(a)

(b)

Figure 5.4: Water jet cutting on superchilled salmon fillet with skin was very good (a) the saw dust in the salmon fillets increased by applying higher transverse speed (b)

5.6 Experiment VIII – Cooled salmon fillets with skin

The cut was overall good, but by increasing the transverse speed the saw dust in the fillets increased (Figure 5.5a). The saw dust is more visible in salmon fillets compared to cod fillets due to the color of the fillet (Figure 5.5b). The water jet was not able to cut through bones and if the jet ended on bones the water beam was not able to cut through the fillet. The water jet pressure was getting little bit better through fillets with pressure of 3500 bar compared to pressure of 2500 and 3000 bar. Orifice diameter of 0.12 and 0.15 mm resulted in cleaner cut compared to orifice diameter of 0.17 mm. Transverse speed of 300 and 450 mm/s was getting better through fillets than transverse speed of 600 and 750 mm/s.

(a) *(b)*

Figure 5.5: Salmon potions after water jet cutting (a) the saw dust in salmon fillets (b)

5.7 Superchilled vs. cooled cod fillets

For the experiments done in Marel, the fillets were placed in a frozen storage before water jet cutting which resulted in lower temperature (>-2 ˚C) than fillets that had gone through CBC cooler. This can led to too low temperature making the water jet cut not able to get through fillet that are too frozen. The results showed that the difference between superchilled and cooled fillets was mainly in the firmness of the superchilled fillets which resulted in cleaner and better cut quality. The tail portion for the superchilled fillets was getting better through the fillet than cooled fillets. The jet was getting better through connective tissue when lower transverse speed was used (150 mm/s) compared to transverse speed of 300 and 450 mm/s (Table 5.7).

In some of the experiment the difference between superchilled and cooled fillets was not high, but the cut quality was though always a little bit better for the superchilled fillets. For both cooled and superchilled fillets, lower transverse speed resulted in the best cut quality and by increasing the transverse speed the saw dust in the fillets increased. The cut was best through the belly flap compared to tail portion and the loin were saw dust and connective tissue.

Table 5.7: Evaluation grades for Superchilled vs. cooled fillets (standard deviation (+/-))

Orifice diameter (mm)	Cooling	Skin	Speed (mm/s)	Cut through Connective tissue	Force to separate connective tissue	Saw dust in fillet	Muscle cut clean	Skin cut through filllet	Force to separate skin	Cleanness of skin cut	Tail portion, Tail trimming, Middle, Belly flap, Loin
0.12	Cooled	With skin	150	0	0	0	0	0	0	0	Tail portion
			150	1	1	0	1	0	0	0	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	1	1	0	0	0	0	0	Tail portion
			300	1	1	1	1(+/-1)	1	1	0	Middle
			300	0	0	0	0	0	0	0	Belly flap
			300	0	0	3	2(+/-1)	1	1	1	Loin
			450	2	2	0	1(+/-1)	0	2	0	Tail portion
			450	1(+/-1)	1(+/-1)	1	1(+/-1)	1	1	0	Middle
			450	1(+/-1)	1(+/-1)	1(+/-1)	2(+/-1)	0	0	0	Belly flap
			450	0	0	3	3	2(+/-1)	2(+/-1)	1	Loin
0.15			150	0	0	0	0	1	0	0	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	1(+/-1)	1(+/-1)	0	0	0	0	0	Tail portion
			300	1(+/-1)	1(+/-1)	1(+/-1)	0	0	0	0	Middle
			300	0	0	0	0	0	0	0	Belly flap
			300	1(+/-1)	1(+/-1)	2(+/-1)	2(+/-1)	2	0	0	Loin
			450	2(+/-1)	2(+/-1)	0	1	1	0	1	Tail portion
			450	2	2	1	1	0	1	1	Middle
			450	0	0	0	0	0	0	0	Belly flap
0.12	Super chilled	With skin	150	0	0	0	0	0	0	0	Tail portion
			150	0	0	1	1	0	0	1	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	0	0	0	0	0	0	0	Tail portion
			300	1(+/-1)	1(+/-1)	1	1	0	0	0	Middle
			300	0	0	0	0	0	0	0	Belly flap
			300	0	0	3	1(+/-1)	1(+/-1)	1(+/-1)	1(+/-1)	Loin
			450	2	2	1(+/-1)	1	0	0	1	Tail portion
			450	2	2	1(+/-1)	1	0	2	1(+/-1)	Middle
			450	0	0	1	1	1	0	1(+/-1)	Belly flap
0.15			150	0	0	0	0	0	0	0	Tail portion
			150	0	0	0	0	0	0	0	Middle
			150	0	0	0	0	0	0	0	Belly flap
			300	0	0	0	0	0	0	0	Tail portion
			300	1	1	0	1	0	0	0	Middle
			300	0	0	1(+/-1)	1	2	1	1	Belly flap
			450	0	0	0	0	0	0	0	Tail portion
			450	1	1	1	1	1	1	1(+/-1)	Middle
			450	0	0	1(+/-1)	1(+/-1)	0	0	0	Belly flap
			150	0	0	0	0	0	0	0	Tail portion
			150	0	0	0	0	0	0	0	Middle

5.8 Trimming of fillets

The result from manual trimming and portioning showed that the loin part weighed highest (47,9%), which is the most expensive part of the fillet. When the pin bones are removed some flesh follows the pin bones (5.1%), and it is important to have the percent of this part minimized (Table 5.8a). There was some variation in the weight of each part between the fillets (Figure 5.6a). Fillets also included some other parts, due to handling and filleting defects (failures). These parts include debris, which accounts for the rest of the fillet after all bones and main parts along with blood of the fillets has been taken, loin bone, rib, blood, fin bone and back spine that were not included in all of the fillets. Trimmed fillet is the total weight of loin, middle lower cut, belly flap and tail which accounts for 89% of the total weight of the fillet. Frequency indicated how many times each part was found in the total of 50 fillets in table 5.8b shows for how many fillets, each part counted, where debris was found in 31 fillets of the total of 50 fillets.

Table 5.8: Average of the weight of each portion, highest and lowest values, standard deviation and frequency for the most common parts of the fillet (a) the parts that are not that common and frequency shows for how many fillet each part counted (b)

(a)

	Tail (%)	Belly flap (%)	Loin (%)	Middle lower cut (%)	Pelvic bone (%)	Pin bones (%)	Tail trimming (%)
Average	13.8	15.2	47.9	14.1	0.7	5.1	1.4
Min:	8.2	12.0	42.8	8.2	0.0	3.1	0.9
Max:	19.2	19.7	52.3	19.8	3.0	7.3	2.2
Standard deviation:	2.8	1.6	2.2	3.4	0.4	0.8	0.3
Frequency:	50	50	50	50	45	50	49

(b)

	Debris (%)	Loin bone (%)	Rib (%)	Blood (%)	Fin bone (%)	Back spine (%)
Average	1.4	1.3	0.9	1.3	1.0	0.5
Min:	0.1	0.3	0.3	0.3	0.2	0.4
Max:	3.6	4.1	1.7	2.6	1.8	0.5
Standard deviation:	0.8	1.1	0.4	0.9	0.5	0.1
Frequency:	31	19	13	6	7	3

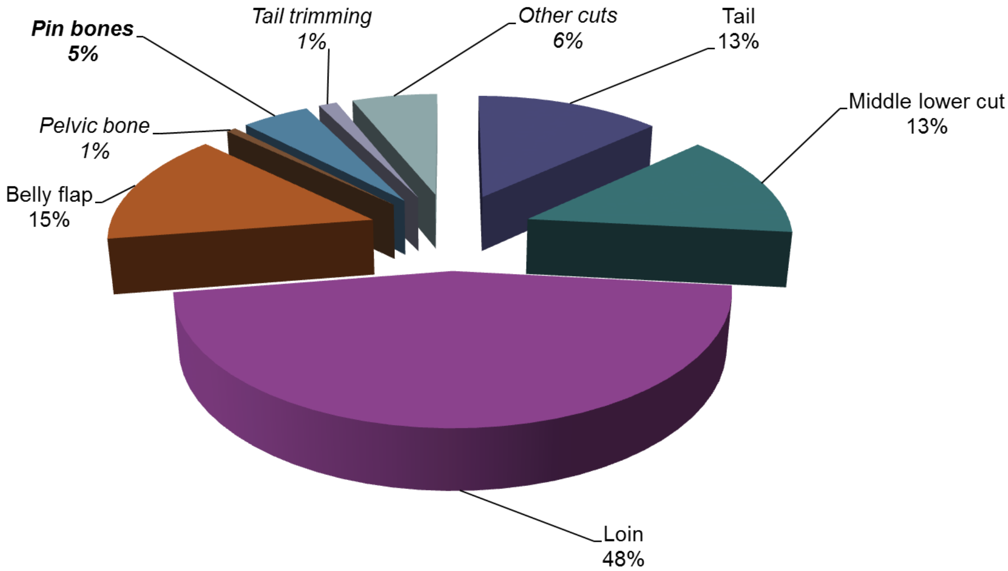


Figure 5.6: The distribution of average percent of each portion of the main parts of the fillet

The result showed that by cutting as close to the pin bones as possible resulted in average of pin bone removal of 2%. It takes more time and precision to be able to lower down the material loss in the pin bone area. To be able to lower the percent down detection of bone location needs to be good to determine the size of the bones and with the advent of the x-ray in the FleXicut it will be possible. Comparison to the experiment before were pin bone removal was in average 5%, the percentage was able to lower down the average pin bone removal by 3% percentage points or down to 2%. The loin weighed highest in average (46%) and the rest counted rather high in this experiment (39%) (Figure 5.7).

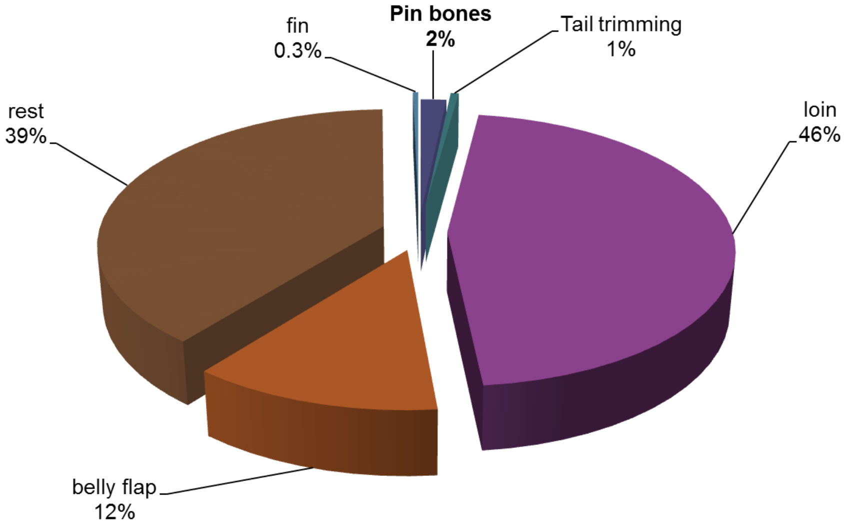


Figure 5.7: The portioning of the trimming in average

5.9 Duration of processing

It took the fillets around 24-25 minutes to go through the process from the beginning, where the fish was headed, filleting, cooling (liquid cooling and CBC cooler) until after skinning. The temperature in the fillets was taken during three steps of the process: gutting, heading and filleting were temperature in the fillets was around 3 ˚C. The temperature in the immersing brine (LIC) was -0.4 ˚C and after the fillets had been in the immersing brine the fillets had the temperature of 0.5 ˚C to 0.7 ˚C. The core temperature in the fillets after the CBC cooler was around -1 ˚C to -0.5 ˚C.

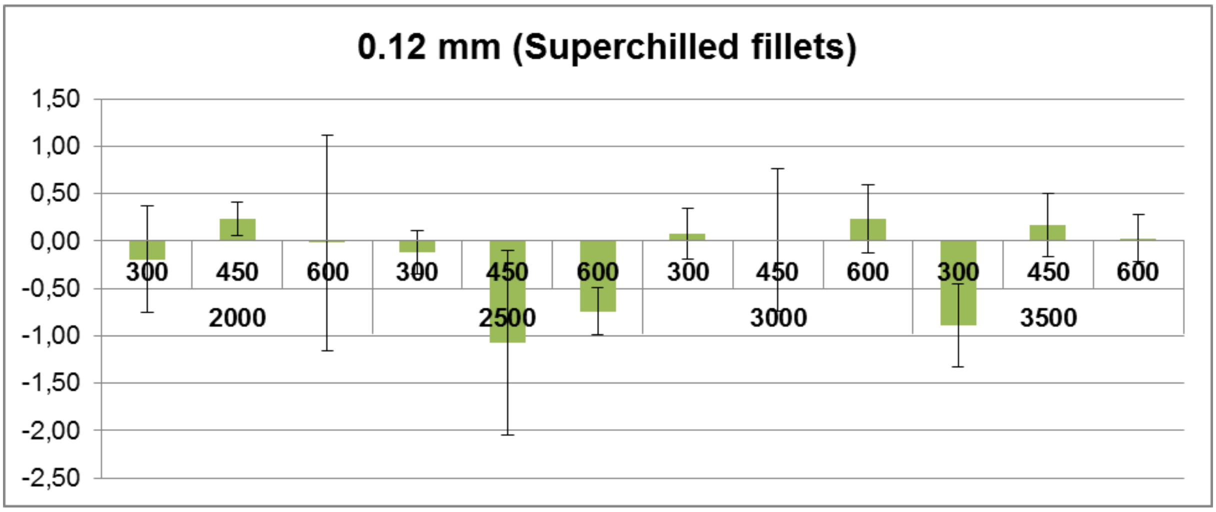
5.10 Utilization (kerf width)

5.10.1 Kerf width and weight yield (%)

The kerf width was difficult to calculate because in the experimental process the loss was assessed from weight loss and not from the thickness of the fillets that would give more acquired results. The weight of the fillets did vary from each experiment so it was hard to estimate the results. The fish fillet bends when the jet cuts through the fillet that result in less kerf loose compared to hard material.

In the experimental process, different orifice diameters were tested to find out which orifice diameter resulted in the lowest kerf loss. To see the difference between orifice diameters the weight before and after the cut were compared to see how much kerf loss was. Orifice diameter of 0.12 mm and 0.17 mm were compared by having the same transverse speeds 300, 450, and 600 mm/s and water jet pressures of 2500 and 3500 bar. The results showed that the lowest kerf loss was when the water jet pressure was 3000 bar and the transverse speed 450 mm/s was used for both orifice diameter of 0.12 mm and 0.17 mm. The standard deviation was high making it hard to estimate where the lowest kerf loss was (Figure 5.8). To see if there was a difference in kerf loose between cooling conditions (superchilled and cooled) orifice diameter of 0.17 mm for two different experiment were superchilled fillets were used and otherwise cooled fillets. The results showed significant different in kerf loos between these two cooling methods where superchilled fillets had lower kerf loss compared to cooled fillets. The values are low and the standard deviation is high which makes it hard to estimate what the kerf loos is (Figure 5.9). Other setting can also influence the kerf loos like the thickness of the fillets where the fillet is thickest in the loin part and the saw dust in the fillets increased when cutting with water jet through the loin part of the fillet.

(a)



(b)

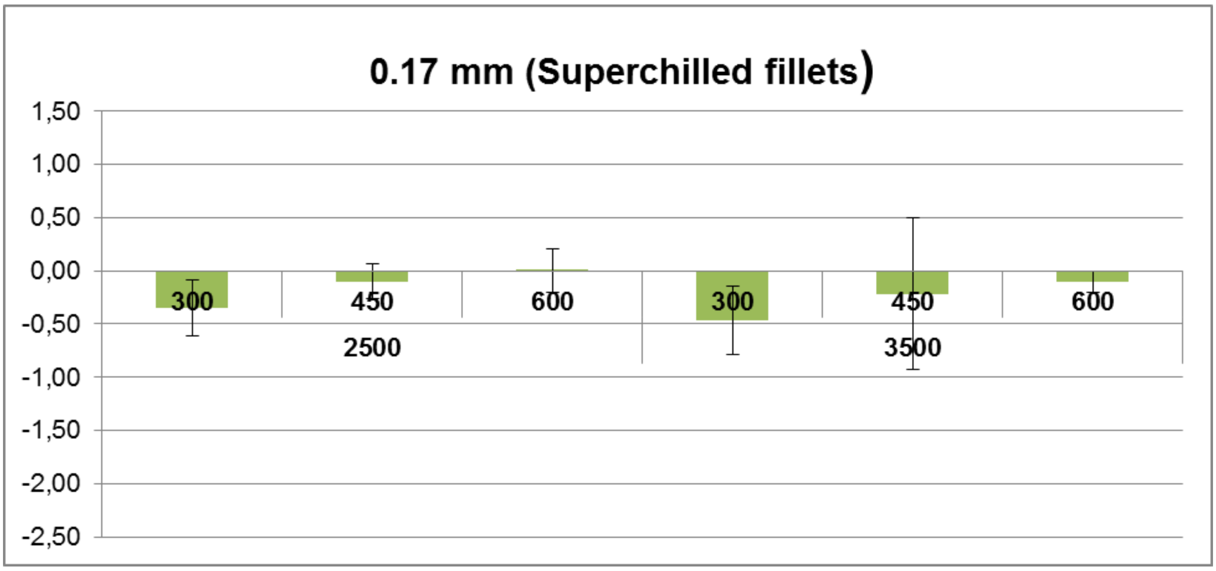
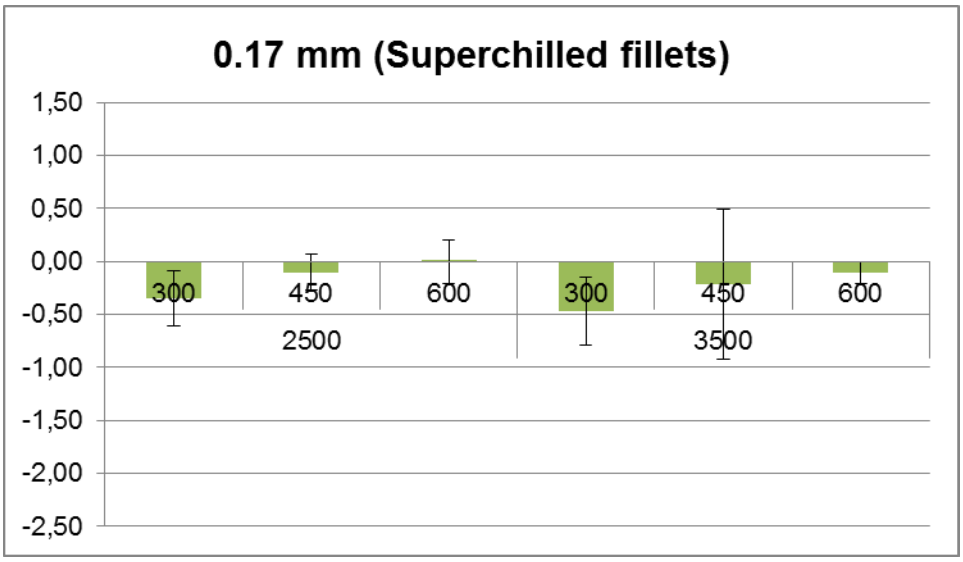


Figure 5.8: The percent change for superchilled fillets with orifice diameter of 0.12 mm (a), and orifice diameter of 0.17 mm (b)

(a)



(b)

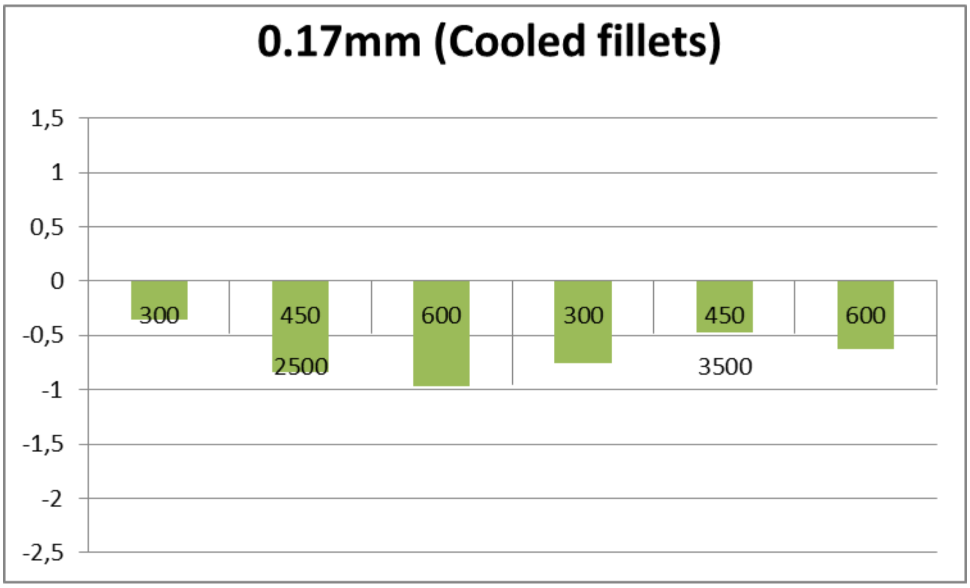


Figure 5.9: Comparison of cooled fillets (a) with orifice diameter of 0.17 mm and superchilled fillets (b) with the same orifice diameter

Results showed that for most cases the weight difference was few grams when comparing the weight before and after the cut. For some fillets the fillet weight increased which might be because of inaccuracy in weight or that some flesh was left on the weight. In the experiment done May 28, 2013 the weight before and after the cut was measured and compared to see the proportional change in weight in percent. In most cases the different was just few grams but increased by 1,8 grams that might be because of inaccuracy in weight or water from the water jet was affecting the weight of the fillet. Particles in the fillets that are loose can also be lost. In average, the proportional change was

1.8% decrease in weight after the cut for the cod (Table 5.9), and 1.6% decrease in the weight for the salmon fillets (Table 5.10).

Table 5.9: Proportional changes of weight of cod fillets during and after the water jet cut

	Weight before the cut (grams)	Weight after the cut (grams)	Proportional change
Average	621,4	609,5	1,0
Max	759,8	744,4	1,0
Min	393,1	385,7	1,0
Standard deviation	139,4	134,9	0,0

Table 5.10: Proportional changes of weight of salmon fillets during and after the water jet cut

	Weight befor the cut (grams)	Weight after the cut (grams)	Proportional change
Average	1007,8	991,2	1,0
Max	1063,1	1046,9	1,0
Min	952,4	935,5	1,0
Standard deviation	78,3	78,8	0,0

5.10.2 Different configuration (pressure/speed and cutting location)

The transverse speed that was applied in these experiments was from 150 mm/s and up to 900 mm/s had great impact on the quality of the cut. The transverse speed of 150 mm/s resulted in good quality cut but fewer cuts that leads to slower processing. For both the loin and the tail portion, transverse speed in the range from 300 to 600 mm/s is preferable. By increasing the transverse speed up to 750 mm/s for these portions saw dust in the fillets would increase. The tail cut was the biggest issue for cod fillets were the connective tissue was strong and hard to ensure that the jet was getting through the fillet each time. The belly flap was not an issue since the cut was getting well through in almost all cases having little or no saw dust in it. The water jet transvers speed could then increase up to 900 mm/s but to receive the best quality cut transverse speed of 450 to 750 should be applied (Figure 5.10).

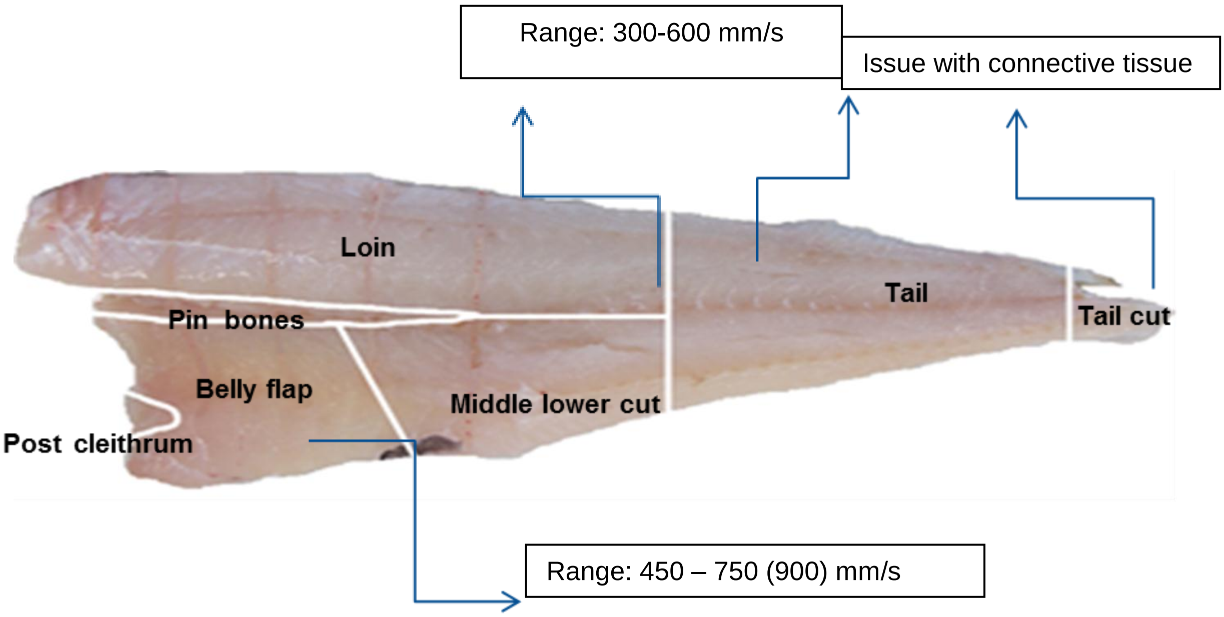


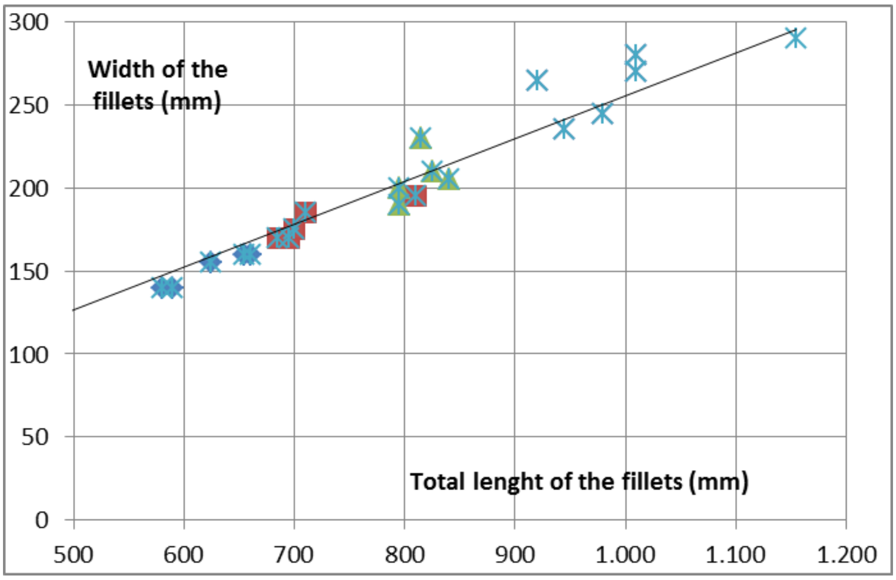
Figure 5.10: Water jet cutting locations along with optimum running range for the transverse speed

Water jet pressure did not have great impact on the cut and we were able to cut with pressure from 2000 to 3500 bar. Results showed that best performance was obtained when pressure of 2500 to 3500 bar was applied.

5.10.3 Size of the fish

The size and weight of the fillet was quite variable between experiments. The weight of the fillet did vary between fillets and in some cases the weight change was rather high. From the five experiments done in July, the average size in the superchilled fillets without skin was 17 cm in width and 49 cm in length. The width and length of the superchilled ones were 17 cm and 50 cm and 18 cm and 53 cm for the cooled fillets, respectively (Figure 5.11).

(a)



(b)

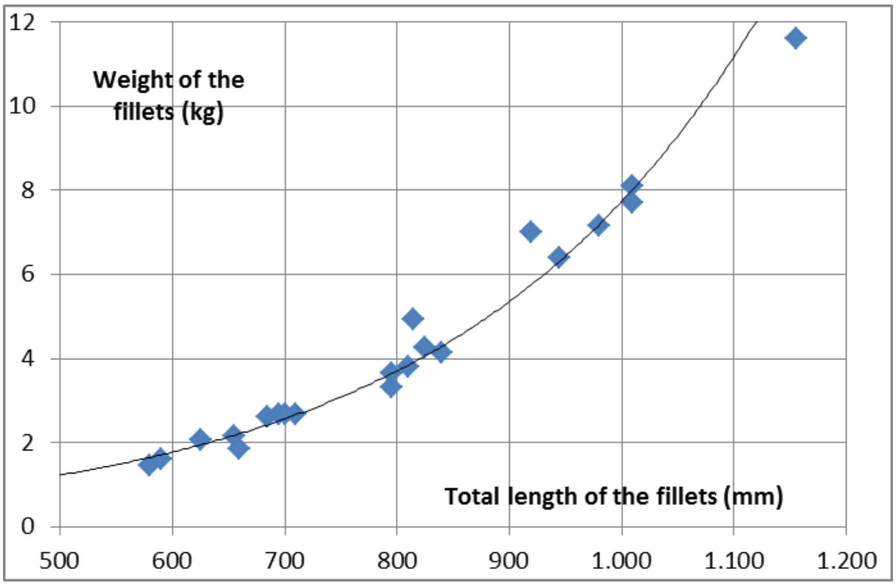


Figure 5.11: Distribution of the width and length of cod fillets (a) and the distribution of the weight and the length of cod fillets (b)

The thickness of the fillets was usually not measured for each and every experiment, but for one of the experiment the thickness was measured and was around 2 to 2.5 cm for fish fillets that were about 700 grams in weight and 50 cm in length (Figure 5.12).

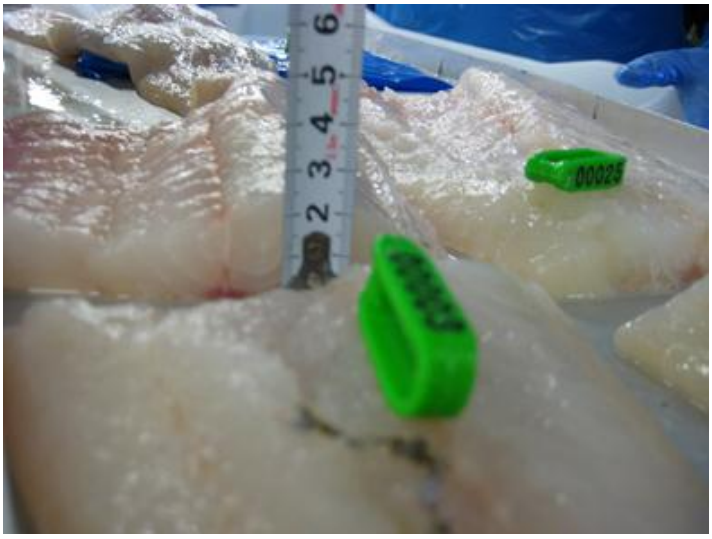


Figure 5.12: Measurement for fillet thickness

6 Discussion

Preliminary test showed that cutting efficiency with water jet varied among the fillets on various settings, like size, length and thickness of the fillets and connective tissues. The transverse speed, orifice diameter and the water jet pressure effects are higher in comparison to the standoff distance of the nozzle.

6.1 Effects of different transverse speed and pressure

The transverse speed is very important when it comes to water jet cutting and results showed that by increasing the transverse rate, that the quality of the cut decreased and saw dust in the fillet increased. Using lower transverse speed down to 150 mm/s resulted in acquired cut and with little or no saw dust in the fillet. On the other hand slower transverse speed resulted in slower processing which means that the water jet is not working fast enough to reach the goal of faster production. It is important to increase the transverse speed in the process to higher the productivity, which led to more profit for the company (Shimizu, 2011). Best quality cut, by maintaining high cutting speed would then be from 300 to 600 mm/s for the tail portion and loin that would result in minimized saw dust and fast production. There is a big difference between 300 mm/s and 600 mm/s, so transverse speed closer to 600 mm/s is preferable, so the production would be able to increase the production flow. In the belly flap, little or no sawdust was in the fillet although high transverse speed was applied, meaning that higher transverse speed could be used for cutting the belly flap. Transverse speed up to 900 mm/s was tested and could be used to cut the belly flap but the best cuts were in the range from 450 to 750 mm/s. The transverse speed also had some effect when cutting fillets with skin where the skin quality increased when slower transverse speed was applied.

The connective tissue was the main problem especially for cod fillets in the tail because the tail contains more and stronger connective tissue than towards the head of the fillet (Hultmann, 2003). The fillet was hanging together usually on the ventral and dorsal side of the horizontal septum and it depended on the size and thickness of the fillet how strong the connective tissue was hanging together (Figure 5.1b). In salmon fillets the connective tissue was not as strong and the water jet cut was getting better through the tail portion in the fillet. The jet was getting better through connective tissue when lower transverse speed was used (150 and 300 mm/s) compared to transverse speed from 600 mm/s and higher.

The pressure did not have has big effect on the cut like expected. The results showed that pressure of 2000 bar was able to get through the fillet but best results were between pressures of 2500 and 3500 bar. There was a big difference in noise from 2500 to 3500 bar that can matter when the water jet is used in the processing plant. The noise level needs to be suitable for people that are working there. For some of the experiments pressure of 3500 bar worked better compared to pressure of 2500 bar in cutting efficiency and cut quality.

For the evaluation of each fillet grades were used to rank the cut, grades were evaluated with the score of 0-4 giving the score 0 representing the best quality and the score of 4 representing the worse possible quality. In general increasing the transverse speed or lowering water jet pressure resulted in higher grade, which means more saw dust and decrease in cut quality. Using larger orifice diameter often resulted in worse cut with particles coming from the fillet.

6.2 Drip loss

The water jet orifice diameter was getting better through fillets with orifice size less than 0.15 mm compared to orifice diameter of 0.17 mm and 0.2 mm, like was tested in these experiments. The Kerf width is the measurement of meat loss is normally reduces as the jet cuts into the meat, so that the kerf width at the lower portion is smaller than that at the upper portion of the cut (Wang & Shanmugam, 2009). Using smaller nozzle smaller kerf width can be obtained (Giedra, 2013). Using orifice with diameter of 0.15 mm, resulted also in less kerf loose in material since the jet is smaller and therefore having cleaner cut. The kerf loss was also less in fillets that were superchilled compared to cooled fillets, but because of low values and high standard deviation it was hard to estimate the kerf loos.

The stand-off distance of the orifice from the material did not show great impact in the cutting process, but it was decided to have the height 4 cm during most of the experiment.

6.3 Effects of fish temperature

The effect of temperature on both cod and salmon fillets on quality of the cut and the performance of the cut was studied by varying the cooling methods. In the experimental process both superchilled and cooled fillets were tested that had the average temperature of -0.5 °C for superchilled cod fillets and 2.8 °C for cooled cod fillets. For the salmon fillets, the average temperature was -1.3 °C for superchilled fillets and 3.4 °C for cooled fillets. The temperature varied among fillets that were tested together that might be because of different size of the fillets and how quick the fillets can warm up in the processing. In some cases the difference was rather big among the fillets that might influence the inaccuracies of the results. For cod and salmon the chemical composition is quite variable and especially in lipid content (Table 2.1)

The results showed that there is more need for super-chilling for salmon fillets compared to cod fillets because the skin cut and quality of the cut was much better among superchilled salmon fillets. The firmness of the superchilled fillets is also important making the cut easier to get through the fillet and making the later processing like skinning easier.

Overall, the water jet cutting on cod and salmon fillets was able to cut through fillets by removing the pin bones. The water jet is able to lower the risk of cross contamination since the water jet uses no blades (KMT, 2008). The flexibility in cut, safety, effectiveness, hygiene and the process adaptability are some of the advantages the water jet has that outweigh the current limitations (Calabrese, 2011). The water jet is considered efficient in improving utilization and increasing the process, but more optimization is needed with regard to utilization with the prototype of the water jet.

7 Conclusions

The relative effects of transverse speed, pressure, standoff distance, orifice diameter were measured and compared in these tests. Overall, the parameter having the greatest effect on performance was the transverse speed, which also directly effects efficiency. The second strongest parameter was the orifice diameter where orifice diameter of 0.12 and 0.15 mm performance was much better than orifice diameters of 0.17 and 0.20 mm in terms of quality of cut and minimized saw dust. The water jet pressure in the range from 2000 to 3500 bar effected performance in some way, but was not shown to be very influential. The pressure would probably have more effect if the range of pressure applied would be bigger. These tests showed that increasing transverse speed is not necessarily the direct path although the production would be faster. The transverse speed should be kept within a range from 300 and 600 mm/s for tail portion and loin and from 450 and 900 mm/s for belly flap for optimum performance.

Overall, water jet cutting was getting through fish fillets if bones did not interfere and the connective tissue was not an issue. Optimum ranges of transverse speed for each specific part were set with the goal of increasing automation and meet certain standard of cutting quality and performance. Although optimum ranges for running conditions were set more optimization on utilization of raw material is needed.

8 Further perspectives

The prototype of the water jet system has been developed by Marel (Figure 8.1), and since the connective tissue was a big problem especially when cutting the tail in cod fillets it was decided that a knife would cut the tail portion off instead of the water jet. By doing this the risk of not getting through every fillet during each experiment is minimized. The knife would be placed in the end after the fillet has gone through the water jet cutting. It will be decided if manual trimming will be before or after the water jet cut.

A new type of orifice diameter specially made for food industry is now available, that Marel has already ordered. It will be tested and compared with the orifice diameters used in these experiments. This orifice is different from the sapphire orifice and the standard diamond orifice that were used in these experiments in which way that the jet is cleaner all the way down and would than maybe result in better quality of the cut (Figure 8.2). The water stream will be smaller and cleaner all the way down compared to other types of orifice diameter (sapphire and standard diamond orifice). Using the new orifice diameter might results in less saw dust in the fillets and maybe lower pressure can be applied to cut the fish fillets. Lowering the water jet pressure will result in less noise and since the water jet will be placed inside processing which means people will have to be able to stand the noise.

Figure 8.1: Prototype of the water jet that will be tested in January 2014

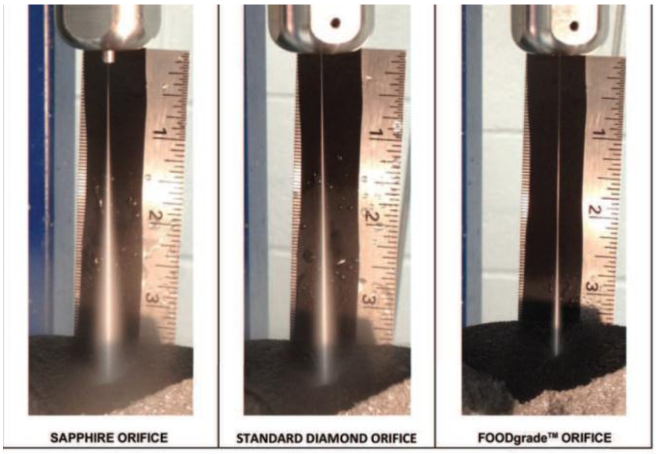


Figure 8.2: Three different types of orifice (KMT, 2008)

The prototype was tested in December 2013 and was working properly where two nozzles are used instead of the one that was used in these experiments. Further test will be made on the water jet in processing to see how the water jet works during full time processing.

With the advent of this machine instead of the manual cutting requires that the whole production process would need to be reviewed. The pre-trimming would most likely occur before water jet cutting where blood spots and worms are removed. Since the tail portion for cooled fillets did go into the gap in some cases if the fillets were not firm enough, it was decided that the loin part of the fillet would enter the water jet first. This was done so the water jet would be able to cut both cooled and superchilled fillets. The tail portion did enter the water jet first in earlier experiment because the fillets come from the filleting machine having the tail portion first, which makes it more suitable to have the tail portion first. This will not affect the processing time since the pre-trimming will most likely occur prior water jet cutting meaning that the fillet would be turned around during inspection. The water jet will contain two lines in the processing plant, one for the right fillets and the other for the left fillets. This is done so the water jet will be able to handle one filleting machine, which takes about 30 fishes per minute. This would mean that the water jet would be able to cut up to 60 fillets per minutes, depending on how good the filleting machine is. Quality control would be placed after the water jet to ensure that market requirements are met and then packaging, storage and transport (Figure 8.3).

In the future the goal is to have a number of processes that are able to work together to reduce loss of weight during fish processing and by doing that increasing the value and quality of the end product.

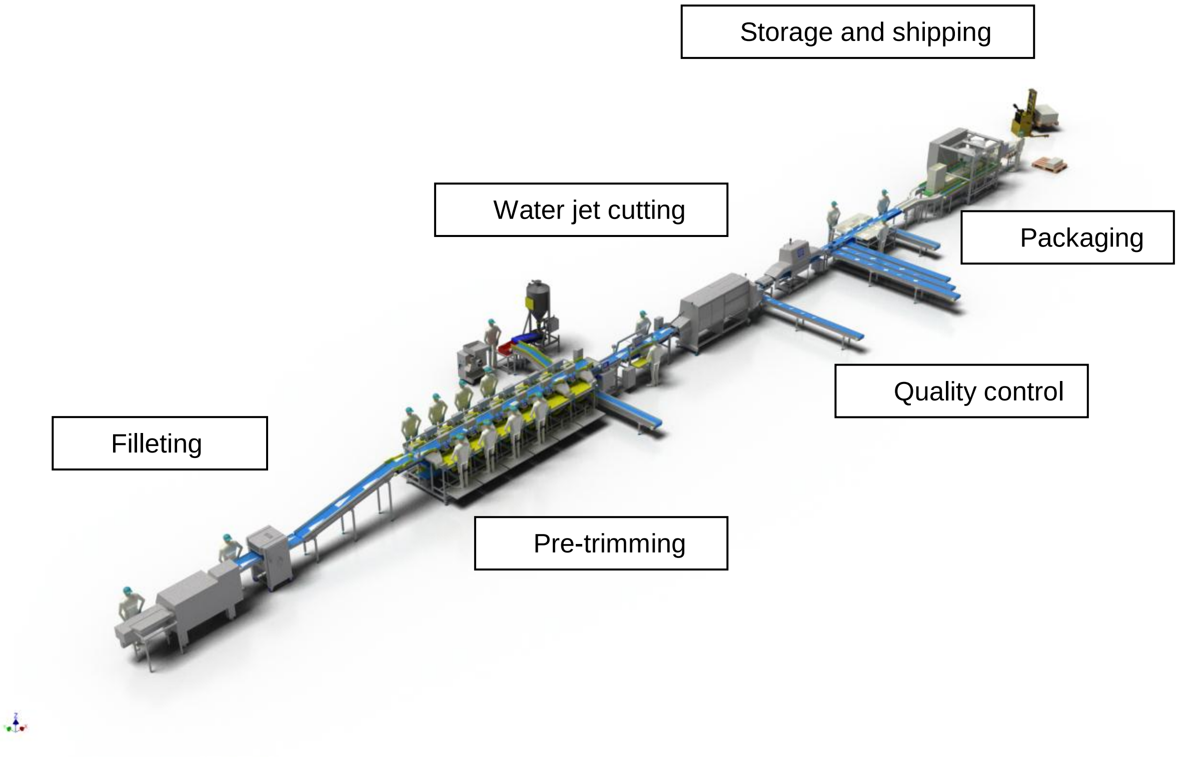


Figure 8.3: Processing plant with the advent of x-ray and water jet cutting

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10 Appendix I

Experiment 12.11.2013 – 13.11.2013 in Marel

Purpose of the experiment:

To cut salmon fillet both cooled and superchilled with 3 different cutting speeds (300, 450 and 600 mm/s), and 2 different pressures (2500 and 3500 bar). The same orifice size 0.15 mm along with the height of the orifice 4 cm was used throughout the whole experiment. The band speed was also the same 0.20 mm and the cutting pattern was double cut.

• Pressure	2500 and 3500 bar
• Orifice size	0.15 mm
• Cutting speed	300, 450, 600 mm/s

Experimental layout:

Seven farmed fishes for each size group (small, medium and big) so total of 21 fishes that were slaughtered in the morning the 12.11.13 from Kalmanstjörn in Reykjanesi were used for this experiment. Each fish was marked and the length, height, and weight of the fish were measured. was measured. After filleting, right and left fillet from the same fish was marked to have the comparison from cooled and superchilled fillets by using fillets from the same fish. The fillets were then placed in the cooler covered with ice over the night. The morning after 13.11.13 the fillets for the super cooling were taken to Esja for the CBC cooler. First the fillets were placed in immersing brine for couple of minutes and then put 2 times through the CBC cooler. Then covered in ice and placed in the freezer in Marel until the experiment started. Fillets were measured before and after the cut with the water jet and temperature were also taken. Couple of cuts will be made on each fillet first the tail portion will be cut and in the end cut with longitudinal cut was made to trim the sides.

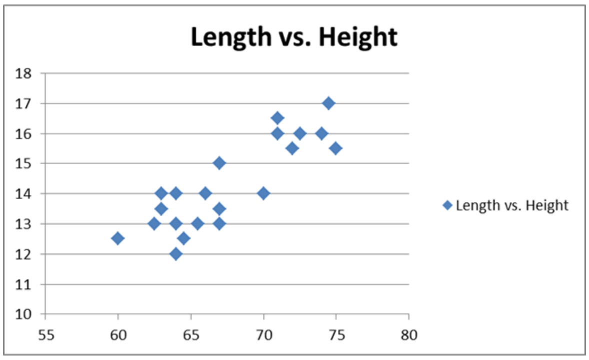


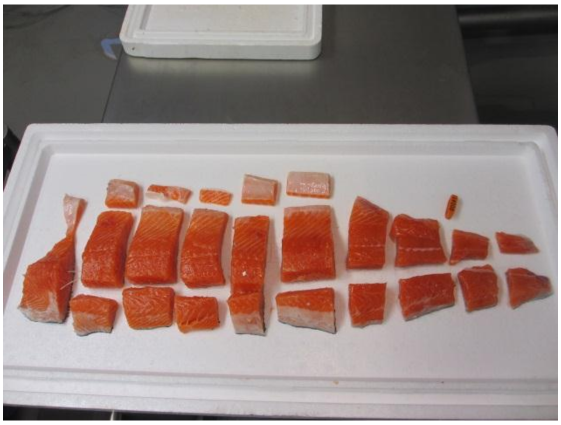
Figure: Height (cm) vs. length (cm) for salmon fillets

Results:

Cooled fillet with tail cut that was getting though in all cases. Clean cut with no sawdust.

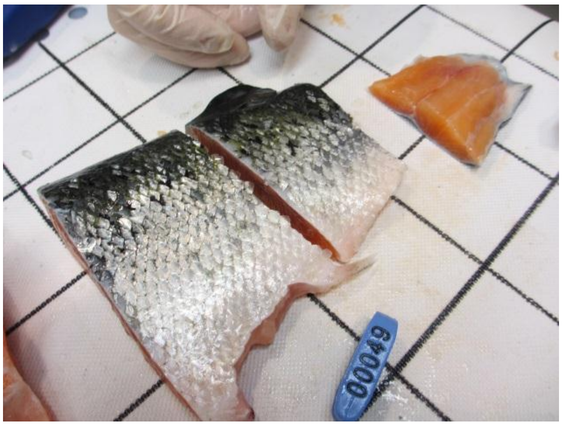
Superchilled salmon fillets showing the quality of the skin cut

Supercooled fillet trimmed cut. The skin cut is clean and cut good.

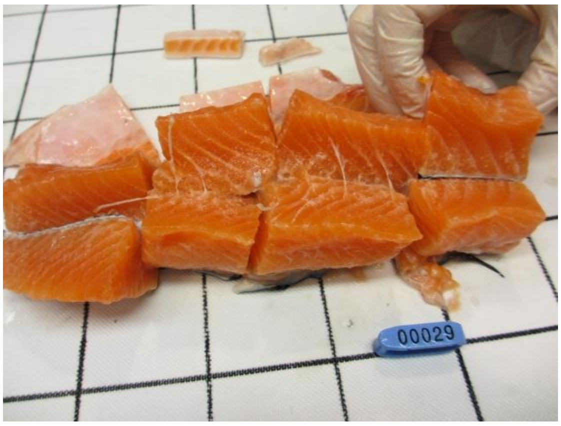


Cooled fillet. Show the fillet after all the cuts.

Cooled fillet trimmed. Cut not getting through the fillet bones are in the way. Little sawdust in the fillet.



Superchilled tail portion cut. Shows the tail is easily getting through and no sawdust in the fillet.



Superchilled trimmed fillet. The cut is not getting through mainly because of bones, sawdust in the fillet.

Cooled fillet trimmed. Bad cut lot of sawdust and connective tissue.

11 Appendix II

Experiment 12.6.2013 in Marel

Purpose of the experiment: Is to cut cod fillet with or without skin both cooled and superchilled with different pressure and transverse speed.

Experimental layout:

To find out the difference in water jet cutting among fillets with different cooling and either with or without skin it was decided to use 40 cooled skinless fillets, 8 superchilled either with or without skin and 20 cooled fillets with skin. The fish was caught the day before in the east right outside Norðfjörð. The fillets were weighted both before and after the water jet. The cutting speed was driven from

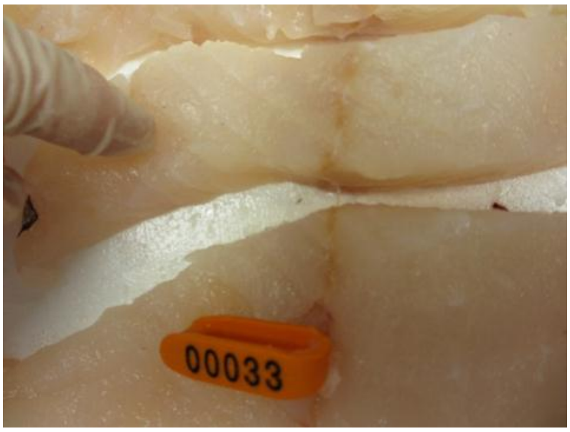
Results:

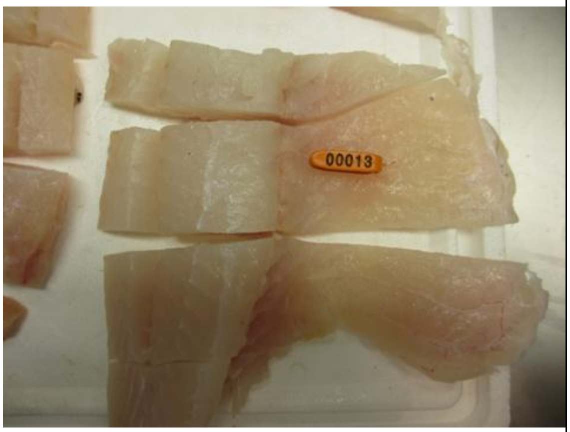
1. **Cooled cod fillet with skin**
2. **Pressure 3500 and transverse speed 600 mm/s**
3. **Cut not getting through**
4. **Hanging together on the pin bones**

Picture 1

1. **Cooled cod fillet with skin**
2. **Pressure 3500 bar, transverse speed 450 mm/s**
3. **Not getting through the skin**
4. **Hanging together on the connective tissue**

Picture 2

<table>
<tr>
<td>
1. Superchilled cod fillet without skin
2. Pressure 2500 bar and transverse speed 450 mm/s
3. Cut almost getting through
4. Cut ended on bones causing the cut not getting through


Picture 3
</td>
<td>
1. Superchilled cod fillet with skin
2. Pressure 3500 bar and transverse speed 450 mm/s
3. Hanging together over the pin bones area
4. Otherwise getting through the fillet


Picture 4
</td>
</tr>
</table>

12 Appendix III

Experiment done June 12, 2013

Purpose: Two cut four salmon fillets two superchilled and two cooled

Experimental layout: To see how the water jet cut was getting through salmon fillets both superchilled and chilled. The superchilled fillets had the temperature of -1,2 °C and -1,4 °C and cooled fillets with temperature around 4 °C.

Results:

<table>
<tr>
<td>

1. Superchilled salmon fillet with skin
2. Pressure 3500 bar, orifice diameter of 0,17 mm and transverse speed of 600 mm/s
3. Is not getting through the skin
4. The fillets is too frozen


</td>
<td>

1. Superchilled salmon fillet with skin
2. Pressure 3500 bar, orifice diameter 0,17 mm and transverse speed of 600 mm/s
3. Not getting through fillet too frozen
4. Saw dust in the fillet


</td>
</tr>
</table>

1. Cooled salmon fillet with skin 2. Pressure 3500 bar, orifice diameter 0,17 mm and transverse rate 600 mm/s 3. Is getting through the fillet in almost all cases	1. Cooled salmon fillet with skin 2. Pressure 3500 bar, orifice diameter 0,17 mm and transverse rate 600 mm/s 3. Is getting almost through the fillet 4. Some saw dust in the fillet
	

13 Appendix IV

Experiment June 12, 2013

Experiment: 40 cooled fillets without skin, 8 superchilled fillets, and 20 cooled fillets with skin. Weight was measured before and after the cut to see the proportional change.

Results:

The weight did not change much is most cases. The difference was little or none but for some fillet the weight increased. Might be water from the water jet and inaccuracy in weight of the fillets.

Number	Pressure	Speed	Size	Weight before cut [g]	Weight after cut [g]	Weight the day after	Proportional change	Proportional change in %
22	**3500**	**450**	0,12	969,5	950,72	--	0,98	98,1
34	**3500**	**450**	0,12	938,2	924,12	--	0,98	98,5
23	**2500**	**450**	0,12	951,5	939,22	--	0,99	98,7
4	**2500**	**450**	0,12	904,8	906,42	--	1,00	100,2
38	**2500**	**300**	0,15	957,1	927,82	--	0,97	96,9
4	**2500**	**600**	0,15	997,1	968,32	--	0,97	97,1
28	**2500**	**450**	0,15	1229,1	1205,62	--	0,98	98,1
22	**2500**	**450**	0,15	1350,8	1321,52	--	0,98	97,8
11	**2500**	**300**	0,15	1232,6	1210,22	--	0,98	98,2
13	**2500**	**600**	0,15	1350,6	1312,72	--	0,97	97,2
50	**3500**	**600**	0,15	1185,5	1161,82	--	0,98	98,0
17	**3500**	**600**	0,15	987,7	963,22	--	0,98	97,5
6	**3500**	**450**	0,15	1142,1	1117,92	--	0,98	97,9
2	**3500**	**300**	0,15	958,3	939,02	--	0,98	98,0
7	**3500**	**450**	0,15	826	806,22	--	0,98	97,6
32	**3500**	**300**	0,15	844,7	830,12	--	0,98	98,3
32	**2500**	**300**	0,17	827,6	822,3	798,02	0,97	97,0
5	**2500**	**450**	0,17	1010,5	1002,1	981,42	0,98	97,9
33	**2500**	**300**	0,17	979	978,4	953,12	0,97	97,4
3	**2500**	**450**	0,17	912,7	904,9	891,22	0,98	98,5
17	**3500**	**600**	0,17	906,7	902,5	875,52	0,97	97,0
37	**2500**	**600**	0,17	786,1	781,2	763,82	0,98	97,8
31	**3500**	**450**	0,17	1112,3	1110,6	1084,52	0,98	97,7
2	**3500**	**300**	0,17	1087,7	1077	1042,62	0,97	96,8
6	**2500**	**600**	0,17	1116,5	1101,8	1074,92	0,98	97,6
20	**3500**	**600**	0,17	1200,1	1190,7	1164,92	0,98	97,8
15	**3500**	**300**	0,17	1259	1252,3	1230,92	0,98	98,3
14	**3500**	**450**	0,17	1229,2	1219,5	1200,22	0,98	98,4
5	**3500**	**300**	0,2	889,8	884,7	863,82	0,98	97,6
17	**3500**	**450**	0,2	878,3	876,8	849,12	0,97	96,8
33	**3500**	**450**	0,2	849,1	846,9	826,12	0,98	97,5
10	**3500**	**300**	0,2	1048,4	1032,3	1007,82	0,98	97,6
6	**3500**	**600**	0,2	1192,1	1179,2	1153,22	0,98	97,8
16	**2500**	**600**	0,2	1159,1	1147	1127,72	0,98	98,3
35	**3500**	**600**	0,2	1058,2	1050,9	1015,02	0,97	96,6
1	**2500**	**600**	0,2	805	796,7	783,73	0,98	98,4
15	**2500**	**450**	0,2	1194,5	1189,2	1169,62	0,98	98,4
37	**2500**	**300**	0,2	1251,4	1239,5	1211,62	0,98	97,8
14	**2500**	**300**	0,2	1283,4	1268,5	1255,22	0,99	99,0
22	**2500**	**450**	0,2	1379,1	1269,1	1246,62	0,98	98,2

Superchillet fillets									
Nr. fillet	**Pressure (bar)**	**Speed mm/s**	**Size**	**Temperature f/cut w/fin**	**Cut**	**Temperature average (˚C)**	**Weight b/cut**	**Weight a/cut**	**Proportional change**
11	3500	450	0.17	-0,8	Þvert	-0,8	925,3	911	0,02
13	3500	450	0.17	-0,8	Þvert	-0,8	1100,5	1080	0,02
22	2500	450	0.17	-0,8	Þvert	-0,75	1329,1	1277	0,04
33	2500	450	0.17	-0,8	Þvert	-0,75	954	930	0,03
4	3500	450	0.17	-0,7	Þvert	-0,65	860,1	850	0,01
38	3500	450	0.17	-0,8	Þvert	-0,8	859,6	849	0,01
11	2500	450	0.17	-0,9	Þvert	-0,85	1032,3	1008	0,02
22	2500	450	0.17	-0,9	Þvert	-0,8	1004,9	988	0,02

Cooled fillets with skin									
Nr. fillet	**Pressure (bar)**	**Speed mm/s**	**Size**	**Temperature f/cut w/fin**	**Cut**	**Temperature average (˚C)**	**Weight b/cut**	**Weight a/cut**	**Proportional change**
28	2500	450	0,2	1,5	Þvert	1,55	1052	1025	0,02
22	2500	600	0,2	0,7	Þvert	1,25	1050,9	1032	0,01
18	2500	300	0,2		Þvert		968,5	958	0,01
31	2500	300	0,2		Þvert		1011,6	995	0,02
1	3500	300	0,2	2,1	Þvert	1,8	960,9	949	0,01
16	3500	300	0,2	1,8	Þvert	1,95	957,8	942	0,02
33	2500	450	0,2	1,3	Þvert	1,35	910,6	902	0,01
10	2500	600	0,2	0,7	Þvert	1	1000,4	981	0,01
37	3500	450	0,2	1,8	Þvert	1,95	1056,3	1044	0,01
5	3500	450	0,2	1,7	Þvert	1,55	1081,2	1064	0,02
4	3500	450	0,17	4,1	Þvert	4,1	1326,7	1314	0,01
15	3500	450	0,17	2,8	Þvert	2,8	1259,8	1242	0,01
48	3500	300	0,17	1,6	Þvert	2,2	1367,2	1348	0,01
23	3500	300	0,17	3,1	Þvert	3,1	1326,9	1306	0,02
20	3500	600	0,17	2,6	Þvert	1,8	895	880	0,02
14	2500	450	0,17	2,5	Þvert	2,5	858,2	859	0,00
42	3500	600	0,17	2,5	Þvert	3,25	1402,6	1380	0,02
41	2500	450	0,17	2	Þvert	2	1312,8	1266	0,04
49	2500	450	0,17		Þvert		1216,1	1200	0,01