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Development of a simulation model for combined Air Drying and Heat Pump Assisted Drying System for Clip Fish

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CHAPTER 1
INTRODUCTION

1 INTRODUCTION

1.1 Summary

Norway is a major exporter of cod in the world and therefore the cod industry is one of the most important in its economy. This is why an important part of the industry is focused on the treatment and drying of the fish, for optimal preservation of food.

This final Master's Thesis is focused on performing a simulation to calculate and define the parameters that involve the drying process. The parameters in the drying process can be designed and controlled to achieve the best performance of the drying process, so that the final product achieves the desired quality within an economically suitable production.

The drying process studied in this work is a combined process of a hot air drier and a hot air source heat pump, so the process can be optimized when the outdoor temperatures are not adequate for the drying.

It has been observed throughout the simulations that the optimal parameters for the drying process are high temperatures and low relative humidity of the hot air and high air velocity. These parameters achieve higher drying rates. The values of such parameters are limited according to quality of the product, heat pump and energy requirements, economic aspects, etc. The results of these simulations have been compared to actual experimental work. In addition, an economic study has been made, comparing the studied system with a traditional one.

1.2 Sammendrag

Norge er en stor eksportør av torsk i verden og derfor torskenæringen er en av de viktigste i økonomien sin. Det er derfor en viktig del av industrien er fokusert på behandling og tørking av fisken, for optimal konservering av mat.

Denne siste Masteroppgave er fokusert på å utføre en simulering for å beregne og definere parametrene som involverer tørkeprosessen. Parametrene i tørkeprosessen kan utformes og styres for å oppnå best mulig ytelse av tørkeprosessen, slik at sluttproduktet oppnår den ønskede kvalitet innenfor en økonomisk egnet produksjon.

Tørkeprosessen undersøkt i dette arbeid er en kombinert prosess med en varmlufttørker og en varm varmepumpe luftkilde, slik at prosessen kan optimaliseres når utendørstemperaturen er ikke tilstrekkelig for tørking.

Det har blitt observert gjennom de simuleringer som de optimale parametere for tørkingen er høye temperaturer og lav relativ fuktighet av den varme luft og høy lufthastighet. Disse parametrene oppnå høyere tørke priser. Verdiene av disse parametrene er begrenset i henhold til kvaliteten på produktet, varmepumpe og energikrav, økonomiske aspekter, etc. Resultatene av disse simuleringene har blitt sammenlignet med den faktiske eksperimentelle arbeidet. I tillegg er det et økonomisk studium foretatt en sammenligning av det studerte system med en tradisjonell en.

1.3 Goals

The main goal of this Master's Thesis is the development of a simulation of a hot air drying system with a heat pump supplemental drying system and the testing of the model. The Engineering Equation Solver (EES) has been used to help develop the simulation.

There have been conducted various simulations with the model created to observe the behavior of the model and the process to different changes in the parameters of the drying process and various combinations of these. With these simulations, an optimal combination of parameters for the process has been obtained.

The results obtained in this theoretical simulation model have been compared to the results obtained in an experimental work so the model can be compared to real data to verify the results.

An economical study has been carried out to observe the investment and operational costs of the combined model.

The chapters that structure this work show the development of the above objectives. In chapter 4, a study of the present drying system techniques is collected, with further explanation of the drying technique selected for this particular work shown in chapter 5. The physical model used for the implementation of the simulation is explained in chapter 6, while the results obtained with the different simulations and the comparison with an experimental model are shown in chapter 7. In chapter 8, there is an economic study including different economical aspects of the drying system, comparing the drying system studied in this work with a traditional one. Finally, conclusions and a note on future work are shown in chapters 9 and 10, respectively.

CHAPTER 2
BACKGROUND

2 BACKGROUND

Codfish consumption throughout the world has increased over the last six decades in a significant way. World per capita food fish supply increased from an average of 9.9 kg (live weight equivalent) in the 1960s to 18.4 kg in 2009. This trend of increasing the consumption of fish in the diet follows the tendency observed of the increased food consumption in general in the world.

Nevertheless, there is still a lot of countries with a deficit in food. Many developing countries continue to face food shortages and nutrient inadequacies, and even inequalities to access to food. Besides, as for the fish, there are great variations regarding the quantity of fish supply and consumption in every region. This is due to customs and traditions respecting the food, the access to fish, the prices, socio-economic levels and seasons.

Although annual per capita consumption of fishery products has grown in developing regions (from 5.2 kg in 1961, to 17.0 kg in 2009) and in low-income food deficit countries (from 4.9 kg in 1961, to 10.1 kg in 2009) *[1]*. However, it is still much lower than in more developed regions, although their consumption is increasing steadily and the gap between developed and developing countries is narrowing.

Throughout history, Norway has been an important fishing nation, due to the proper climate conditions and the long coastline all along the country. Norway has been placed as the second greatest exporter in the world, in fish and fishery products. Increasing a production of 3.533US$ millions in 2000, to 8.817US$ millions in 2010, which means a rising of 9.6 of APR (average annual percentage growth rate) *[2]*. The most important fish stock in Norway have been cod, herring and salmon as well, with an important growth in aquaculture industry, especially of salmon. Fish and its products generate 5.7% of the total Norwegian export value, and are one of Norway's most important export. In 2010, clipfish (salted and dried cod) represented 13.6% of the export value of the fishing industry, and approximately 2.4 million tons of clipfish were exported. The greater part of cod fisheries stocks is used to consumption, while herring fisheries stocks are mainly processed into oil and animal feed.

Since fish exportations in Norway are of great importance because of how large it is, it is necessary a sustainable management of the sea and its resources, achieved through regulations and harvest control rules. Great catches ought to be regulated, since, if not sustainable by the cod population, the stocks of codfish would began to collapse. An integrated management plan for the Barents Sea-Lofoten area has been developed to resolve conflicts between petroleum activities, fisheries activities and to address conservation concerns.

As it has been said before, Norway has a long history of exporting cod around the world. It has been trading codfish since the Vikings (AD 800) Norwegians used dried cod during their travels, and soon a dried cod market developed in southern Europe [3]. Cod fisheries in Norway were developed to transport long distances stockfish (dried cod) and, since the introduction of salt, "klippfisk" (dried salt cod). With the success of the Hanseatic League dominating trade operations and sea transport by the end of the 14th century, Bergen was set as the most important port in the trading routes of the League. Norway has a long-standing tradition of exporting cod especially to "bacalao countries" such as Spain, Portugal, Italy and Brazil [4]

Drying became really important so that cod could remain edible for a long time, which was crucial for transportation. That why food preservation methods started to be developed, and techniques of preservation of food such as drying are of great importance and still are being developed and improved nowadays.

CHAPTER 3
DRYING

3 DRYING

3.1 Background

Food begins to spoil the moment it is harvested. Food preservation enabled man to preserve some of the food for future use, instead of consuming all the harvest immediately. Dehydration can improve palatability, digestibility, color, flavor, and appearance of a food. Food preservation inhibits the proliferation of microorganisms and hinders putrefaction through the removal of water. Moreover, by removing the water, it increases the osmotic pressure by concentrating salts, sugars, and acids, creating a chemical environment unfavorable for the growth of many microorganisms [5].

Throughout history, it has been shown that not only did they dried food like fish and meat. Middle East and oriental cultures dried food in the sun and wind since 12.000 BC. Evidence shows that the Romans dried fruit, and in the Middle Ages they used especial buildings to dry fruit, vegetables and herbs, using a fire when sunlight wasn't enough, to dry and even smoke the food if necessary [6].

Many types of food are suitable to dehydration. For centuries, the main nourishment of the European population was cod, either dried cod, stockfish, or dried salted cod, bacalao. There are also important the dehydration of the tuna, and in certain regions, of shark. Another important dried food is ham, beef jerky and reindeer. Cod is particularly suited for drying, since it barely contains fat, which would become rancid even if dried.

Vegetables change completely their properties when they are dried. The process of drying is rarely used with vegetables since it removes the vitamins they contain. However, it is not rare to dry certain vegetables such as tomato, garlic, onion, pepper, etc. Fruits are also nutritionally inferior and change completely when dried, but it is common to have dried fruits such as prunes, raisins, figs and dates.

The Portuguese were the ones who developed clipfish, which is dried and salted cod. However, salt was expensive for nations of northern Europe, so it was not until the 17th century that salting was economically feasible for northerners to partake in the salting method. Salting is another method to prevent food from spoilage. Salt brings water out of microbial cells through osmosis, thus preventing the growth of microorganisms.

The process of salting and drying the cod consists in two different and separate methods after it is beheaded and eviscerated by the fishermen, normally on board the boat. It starts by keeping the cod in salt, which is a process that lasts for two or three weeks. When the cod is salt-matured is ready to enter the drying process to pass from wet salted fish to clipfish [7].

Drying has changed over the centuries. The name of clipfish comes from the way fishermen used to dry the cod on rocks on the foreshore, since the Norwegian word "klippfisk" literally means "cliff fish". They would dry the cod outdoors by the sun and wind, often hanging on wooden scaffolding or simply lying on cliffs or rocks near the seaside, near the fishing ships. In the North Sea coast, the outdoor drying would only be feasible in spring due to the climate and weather conditions.

Nowadays, the fish is dried indoors with the aid of electric heaters. Drying it indoors offers the advantages of avoiding that the fish gets infected by worms and insects or spoiled with dust and sand as it could be if dried in open places, and being able to control parameters of the process so quality of the fish and drying time can be improved.

The advantages of treating the cod with the salting and drying processes consist on:

- The fish preserves many nutrients after being treated. The process removes the moisture needed for bacteria, yeast and molds to live, whilst concentrating nutrients.
- Extending storage life for several years. Since the water is removed, the microbial activity in the fish decreases, achieving that the fish last longer.

- The salting process makes cod tastier, since apart from adding salty flavor to the fish, it makes the cod more flavorful.
- Cheap method
- When dehydrated, the fish are light and require little space for storage and transportation. Packaging, handling, and transportation of a dry product are then easier and cheaper.
- The salted and dried cod acquires high quality

3.2 Energetics

Regarding the processes comprising the salting drying method, this Master's Thesis is focus on the drying process.

To begin to discuss the drying process, energy processes and parameters involved must be taken into account. There is a heat exchange between the atmosphere and the moisture on the surface of the product, as long as a mass transfer of moisture from the internal layers of the fish to the surface and the posterior evaporation to the atmosphere.

3.2.1 Water activity

One of the most important parameters regarding the drying process is the water activity. The water activity (a_w) is defined as the partial vapor pressure of water in a substance, in this case the cod, divided by saturated vapor pressure of pure water at the same temperature, as in Eq. 3.1.

$$a_w = p/p0 \quad \textit{Eq. 3.1}$$

It is related to the equilibrium relative humidity (ERH), since they refer to the relative humidity of the surrounding atmosphere in equilibrium with food, but a_w is a parameter itself of food, whereas ERH refers to the surrounding atmosphere. ERH is expressed as a percentage, as in Eq. 3.2.

$$ERH = a_w * 100\% \quad \textit{Eq. 3.2}$$

As it has been stated earlier, biochemical reactions and proliferation of bacteria are influenced by the moisture content in the fish. Every microorganism has an optimum and a minimum water activity for growth. Water activity below the optimum decreases the growth rate, and below the minimum totally inhibits the growth. Therefore, the spoilage of a food is directly proportional to the water activity. Substances with higher a_w tend to be spoiled more easily, due to microbial activity. Water activity below 0.50 inhibits microbial proliferation [8].

3.2.2 Bound and free moisture

Water within the food can be bound or unbound to the solids, and this influences the drying process.

Moisture held in loose chemical combination, present as a liquid solution within the solid, which exerts a vapor pressure less than that of pure liquid, is called bound moisture. Moisture in excess of bound moisture is called unbound or free moisture.

In food dehydration, when hot air is used to transfer heat to the food, the temperature and relative humidity of the air determine the final moisture content to which a food can be dried. If the food is left in contact with air at constant conditions for an indefinitely long time, it will reach equilibrium with the air. The moisture content of the food at equilibrium is known as equilibrium moisture content (EMC).

3.2.3 Drying phases

Cod starts with an approximately 80% of water content before it enters the process of salting. This process takes about 3 weeks for the cod to be salt-matured as it has been stated before. Salt-matured fish to be dehydrated is composed approximately of 18-20% of salt, 55-60% of water and 20-27% of salt free dry matter. After the drying process, the fish is thought to be dried when it reaches a total water content minimum, considered to be below 50%. It is sought to be about 43-47%. [9]

In the drying process, water moves from the internal layers of the fish to the surface and is then evaporated due to the transfer of energy from the surrounding environment, in this case, hot air acting as the carrier gas.

The dehydration process can be decomposed in two different drying stages.

- The first phase, when the surface water is removed. Initially, the food product is wet, and moisture moves easily to the surface, thus keeping the surface wet. The moisture removal rate during this phase of drying is constant and is a function of only the air conditions.
- The second phase, when the water from the internal layers of the fish, the water of the loins, is removed by its movement to the surface layer and posterior evaporation. The process is such that the movement of moisture inside the food is slowed down, and the food surface contains dry and wet spots. The moisture is removed at a declining rate from the surface of the food. Eventually, as the evaporation of moisture occurs inside the food material, the removal of moisture is further slowed down.

CHAPTER 4

DRYING SYSTEMS

4 DRYING SYSTEMS

4.1 Sun and solar drying

Sun drying refers to foods that are dried under the direct sun. Sun drying is the old-fashioned way to dry food because it uses direct solar radiation and the natural movement of the air, ambient air temperature and relative humidity. This process is slow and requires continuous care, the food must be protected from insects, covered at night and it cannot be used in rainy periods. Thus, it is a long-drying process, the quality of the final product is low since the conditions and parameters of the process cannot be controlled. However, is the cheapest drying method and does not have special needs of equipment or energy consumption costs, so it is suitable for developing countries with proper weather for the process. The drying time depends on product characteristics and drying conditions but it typically ranges from 3 to 4 days.

A way to reduce sun-drying time with a better quality of the final product is to use solar energy concentrators with or without natural or forced airflow inside the dryer, where heat is transfer by radiation, and in case air is used, by convection as well. This method is called solar drying. Solar dryers can be direct or indirect. In direct solar dryers, the fish is dried in an enclosure with a transparent cover or side panels, whilst in indirect solar dryers the air is preheated in a solar collector to raise the drying air temperature and then ducted to the drying chamber. Construction of solar dryers is simple and requires a relatively low investment cost. [10]

There are hybrid systems using another form of energy to supplement solar energy, such as fuel or electricity, for both heating and ventilation, either in direct or indirect dryers. This auxiliary sources of energy are needed where a large amount of product needs to be dried and during low radiation periods or at night, where the auxiliary heat source is needed to supplement the heat energy.

4.2 Atmospheric hot air dryers

Hot air dryer is a process that uses the atmospheric air as the heat source and moisture carrier. The chamber is equipped with a blower and ducts to allow the circulation of hot air, transferring heat to the product by convection. This is one of the simplest and most economical methods, because the equipment is easy to implement and operate, and has low investment and operating costs. However, hot air drying is a method that requires a long drying time and high energy consumption.

4.3 Heat pump dryer

Heat pump dryers recover the latent and sensible heat from the exhaust gas by condensing moisture from the drying air. This way it increases the energy efficiency by heating the dehumidified drying air with the recycled recovered heat. With other conventional drying methods, this heat recovery would be lost in the atmosphere. This enables drying at lower temperatures, lower cost, and operation even under humid ambient conditions.

With heat pump drying, there is control of the moisture and temperature of the air as well as heat recovery. In this way, heat pump dryer can improve the product quality while using less energy and with less drying time. Any dryer that uses convection as the primary mode of heat input can be fitted with a suitably designed heat pump.

Heat pump drying technology has been combined with other drying techniques to achieve improved product quality, reduced energy consumption, high coefficient of performance (COP), and high thermal efficiency.

Heat pump drying consumes only about half or one-third of the electricity of conventional condenser dryers. HPD had the lowest operating cost when compared to electrically heated convective dryers.[11]

4.4 Osmotic dehydration

Osmotic dehydration consists in the removal of water from lower concentration of solute to higher concentration through semi permeable membrane, resulting in the equilibrium condition in both sides of the membrane. In osmotic dehydration, the solutes used are generally sugar and salt. In this process, water flows from the product to the solution, and along with water, some components of the food such as minerals, vitamins, acids etc. also move towards the solution. To achieve equilibrium, the sugar or the salt migrate towards the food.

Osmotic dehydration has been used as a food preservation method because it is quite simple and less energy intensive than other drying methods (resulting in lower investment and energy costs) since it can be conducted at low or ambient temperatures, and it maintains good quality of the food as well as its initial characteristics like structure, flavor and nutrients. [12]

4.5 Vacuum dryer

Vaccum-drying technologies are used to intensify moisture removal when lower drying temperature is needed to protect heat-sensitive food components. Vacuum drying is similar to freeze drying, which will be later developed, but in vacuum drying the product is not frozen and the vacuum is not as high as in freeze drying. Heat transfer occurs in this process by radiation and conduction. The vacuum dryer system consists in a vacuum chamber where the product is placed, a heat supply, a device for producing and maintaining the vacuum, and components to collect water vapor evaporated from the food. The vacuum drying technique is rarely used to dry fish.

4.6 Freeze dryer

Freeze drying is a special case of vacuum drying. In freeze drying, water is removed at low temperatures (about -10C) and in a vacuum of 0.1 to 2 mmHg since the removal of the moisture is done by sublimating the water without a phase change from solid to liquid.

Freeze dehydration involves two stages. First, the freezing of the food occurs very rapid, where most of the water is converted to ice. Then, the sublimation of the water occurs by transferring heat to the product under a high vacuum environment. The freeze dryer needs a very efficient condenser to remove water vapor from the dryer and a high performance vacuum pump to create vacuum. Heat transfer occurs by conduction and radiation accompanied by a high vacuum sublimation. However, additional microwave or infrared radiation heat is sometimes supplied.

The main advantage of freeze drying is the superior quality of the final product. The structural rigidity of the product is maintained during the sublimation process, little or no shrinkage occurs and products retain better flavor, aroma and most of their properties of their fresh state. Freeze-dried products, when packaged under proper conditions, can be stored for an unlimited period of time. [13]

Nevertheless, freeze drying disadvantage is that it is an expensive process because of to the slow drying rate and the high equipment and operational costs due to the use of vacuum. It is then used for delicate items or expensive products, or food products that may be damaged by heat in other dryers.

4.7 Microwave drying

Microwave drying is primarily used as an additional supplied method for drying. This drying method uses microwaves for moving water from the internal wet layers of the food to the surface, relying on the preferential heating of water by microwaves. A hot air circulation or a vacuum must be provided to transport the moisture that is being vaporized from the surface of the food. It helps reducing drying time due to its rapidity of heating. However, the high cost of energy, since the ratio of the energy absorbed by the product over the energy consumed is very low, especially compared to conventional energy, and the high investment cost of equipment, are the main disadvantage of this drying process. Besides, there is the difficulty of controlling the heating uniformity of microwave drying. The main advantage of the microwave drying is the better product quality, since the final product maintains most of its nutrients and flavors and retains its structure with very little shrinkage or color degradation.

4.8 Radiofrequency drying

A similar drying method to microwave is the radiofrequency (RF) or high-frequency drying, except this method uses lower frequencies. The electromagnetic energy is generated between two electrode plates through which the food is placed or circulated. Unlike microwaves, a good heating uniformity can be achieved. The better wave penetration and energy distribution is partially cancelled by a lower heating capacity due to lower frequency. That fact causes radiofrequency units to be larger than microwave units for a similar power. [14]

4.9 Infrared drying

The origin of infrared is thermal, and its application results in a direct thermal effect. It is mainly used for surface drying because the penetration depth of infrared rays and the uniformly energy distribution are small due to their higher frequency. Products are transported beneath infrared radiators on belts or vibrating plates. Infrared radiation can be produced using two sources of energy: either natural gas (transform into radiant energy with low efficiency) or electricity (with a high efficiency). Infrared drying is used for thin-layer drying of some foods or can be used as a finish drying operation.

4.10 Acoustic drying

Acoustic drying has been applied as an additional energy supplied method in combination of solar drying systems, particularly for drying agricultural products. According to their frequency, acoustic waves can be classified into infrasounds (f lower than 20 Hz), audible sounds (f between 20 Hz and 18 kHz) and ultrasounds (well known as UV, with f higher than 18 kHz). Ultrasounds, which cannot be detected by the human ear, improve drying process efficiency. Acoustic drying method has better performance than convective processes and operates at lower temperatures, which is particularly usefull for drying heat-sensitive food. [15]

CHAPTER 5

COMBINED AIR DRYING AND HEAT PUMP

5 COMBINED AIR DRYING AND HEAT PUMP

Hot air drying method is one of the most economical and simple of the drying methods. However, the process depends too much on the atmosphere conditions and the controllability of the process is low. When the temperature of the outdoor air difficult the drying of the product, additional methods of heating are required to be able to get the demand of hot air needed.

One of the most common supplemental methods for the drying is the heat pump. It can be used when the atmosphere air is not enough to achieve the quality demands of the final product. It is an economic process since, as it has been explained earlier, it leads to energy consumption savings, since the heat pump system recycle the latent and sensible heat of the exhausted air. That way, the high coefficient of performance of the heat pump rises the efficiency of the drying system.

The process can be adiabatic or nonadiabatic, based on the energy source. In adiabatic processes, there is no mass or heat transfer from the outside of the process chamber. In the case of drying, heat of vaporization is supplied by sensible heat of air in contact with the product to be dried. In nonadiabatic processes, the heat of vaporization is supplied by radiant heat or by heat transferred through the walls in contact with the material to be dried.

According to the moisture removal rate, it can be constant or falling rate processes. As it has been explained before, removal of moisture depends on the phase of the process. First, the food is wet on the inside and in the surface. Moisture moves from the inside of the fish to the surface, keeping it wet, where is evaporated and carried by the hot air. The moisture removal rate during this phase of drying is constant and is a function of only the air conditions. As drying continues, the movement of moisture inside the food is slowed down and the food surface contains dry and wet spots. The moisture is removed at a declining rate from the surface of the food. Eventually, as the evaporation of moisture occurs inside the food material, the removal of moisture is further slowed down. In a constant rate dehydration process, the rate of moisture removal remains constant with time, and in a falling rate dehydration process, the rate of moisture removal decreases as the drying progresses. The moisture content of food at which the falling rate period starts is known as the critical moisture content. [16]

Another division of the process is according to the process time. Processes can be divided in batch or continuous processes. In a batch dehydration process, the moisture is removed from a certain quantity of food at a time. The dryer is loaded with the wet food and, after drying, the dried product is removed. The next load of food is then loaded in the dryer, and the process is repeated until the total quantity of food is dried. The batch-drying chambers are rooms that have controlled heating and ventilation. In a continuous dehydration process, wet food material is fed continuously into the drying chamber. The food is dried during travel through the drying chamber, and dried food is collected at the exit. Generally, the process conditions remain steady except during start-up of the dryer or during process upsets. Depending on the direction of flow of both air and food, these types of dryers can be further classified as concurrent, countercurrent, and crossflow dryers. In concurrent dryers, both hot air and food travel in the same direction through the drying chamber; in countercurrent dryers, hot air and food travel in opposite directions; and in crossflow dryers, hot air and food travel perpendicular to each other. [17]

The optimal air stream direction is lengthwise the tunnel in countercurrent direction. Crossflow air flow and air/fish in crossflow direction give a lower production than for a lengthwise air flow and air/fish in countercurrent direction. [19]

This kind of heat pump used in this drying system is the air source heat pump (ASHP). The heat pump produces warm air from the outdoor air, which is circulated by fans to heat the chamber. The heat pump need plenty of space around it to get a good flow of air, preferably on the sunniest wall. Since ASHPs work best when producing heat at a lower temperature than traditional boilers, it is essential that the chamber is insulated and draught-proofed well for the heating system to be effective. One of the advantages of this system is that, although the weather data used in this work is taken from Averøy, at cost of mid Norway, and therefore the temperatures are low, since heat pumps work at low temperatures, this drying system is ideal.

Some of the advantages of the heat pumps are:

- As it has been said earlier, unlike gas and oil boilers, heat pumps deliver heat at lower temperatures over much longer periods.
- Lower fuel cost than when using conventional heating.
- Lower carbon emissions than other conventional heating systems.
- Minimal maintenance required.
- Payback of the ASHP system more quickly than other heating systems.

Heat pump drying system means savings as it has been implied in the advantages. These costs and savings depend on the size of the chamber and how well insulated it is, the requirements of energy and the room temperature aiming to achieve as well as the efficiency of the ASHP. It also depends on the fuel cost, since the heat pump is powered by electricity so it is necessary to pay for the fuel. Savings are improved when the control of the parameters operating the heat pump is good. The better the parameters are for the drying system, the heat pump, and product, the better the efficiency will be, and therefore, better savings will be achieved.

As it has been said, one of the advantages is that the maintenance of the heat pump is minimal. The operative life of an air source heat pump is estimated to be more than 20 years. It is recommended to check oneself every so often a year the heat pump, but a professional from the supplier company should take care of the maintenance every few years.

In the figure below (Figure 5.1) a schematic representation of a heat pump system can be seen, where the different stages of the process cycle are represented. The figure is an extract from the *Handbook of Industrial Drying* [17].

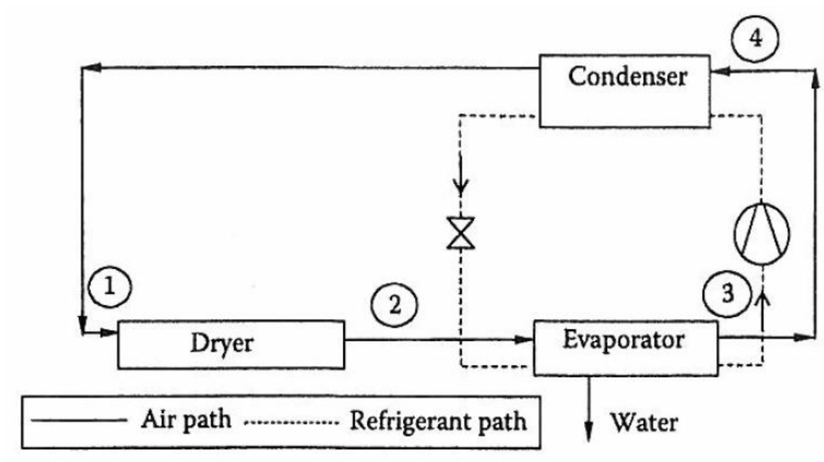

Figure 5.1 Schematic representation of a heat pump system

The heat pump cycle works as follow:

- The hot air enters the chamber of the dryer, at point 1, where it dehumidifies the wet product, and exits the dryer as wet air, ready to enter the heat pump cycle.

- The air enters the evaporator and is cooled and dehumidified moving from point 2-3. The refrigerant in the evaporator absorbs heat from the air and undergoes a two-phased change from vapor-liquid mixture to vapor while maintaining its temperature and pressure.

- The refrigerant vapor enters the compressor at point 3. Electrical energy input to the compressor is converted to work to raise the pressure of the refrigerant vapor to that of the condenser at point 4. At this stage, the vapor is in a superheated state.

- Then, the vapor is directed to the condenser, point 4, which is basically a heat exchanger, to carry out the condensing process after it undergoes a desuperheating change to obtain saturated vapor. During the condensation, where the refrigerant changes frim vapor to liquid phase, heat is rejected by the condenser to the air-to-be heated.

- Heat recovery occurs when the heat energy absorbed in the evaporator and the work energy from the compressor is pumped to the condenser side of sensible heating of the air.

- When the refrigerant exits the condenser, it can undergo a stage of subcooling before the throttling device, to recovered additional heat for sensible heating of the air and to reduce flash in the throttling. After the condenser, a throttling device expands the liquid refrigerant to reduce the pressure of the refrigerant. After the expansion process, the refrigerant enters the evaporator in a two-phase state.

- The cycle repeats itself.

As it has been said before, in the process it is used a countercurrent direction flow dryer, where the hot air flow and the food travel in opposite directions, through the lengthwise of the tunnel. The schematic of the flow with the heat pump system is represented in the continuous process mode in the figure Figure 5.2 below. However, the figure is an extract from the *Handbook of Industrial Drying* [17] and it represents a concurrent drying mode instead of a countercurrent mode, since the inlet and the outlet of the product to be dried have the same direction as the air flowing within the heat pump system. In the case worked here, the inlet hopper would be at the exit of the drying tunnel, while the outlet hopper would be at the entrance of such tunnel. The system used in the work in 1out/1in. If the batch mode were used, when the air entered the chamber, the first fish would get the highest heat transfer to the hot air, getting faster to the desired moisture content of the fish, while the last fish would be encountered with already wet air before it leaves the chamber. That means that the fish closest to the exit of air would exchange little heat and it would take much longer time to dry. With the 1out/1in system, when the first row of fish has reached the desired degree of dehydration is removed from the tunnel, and another wet row is pushed from behind automatically. That way, the heat transfer in the chamber is more effective than in a batch mode.

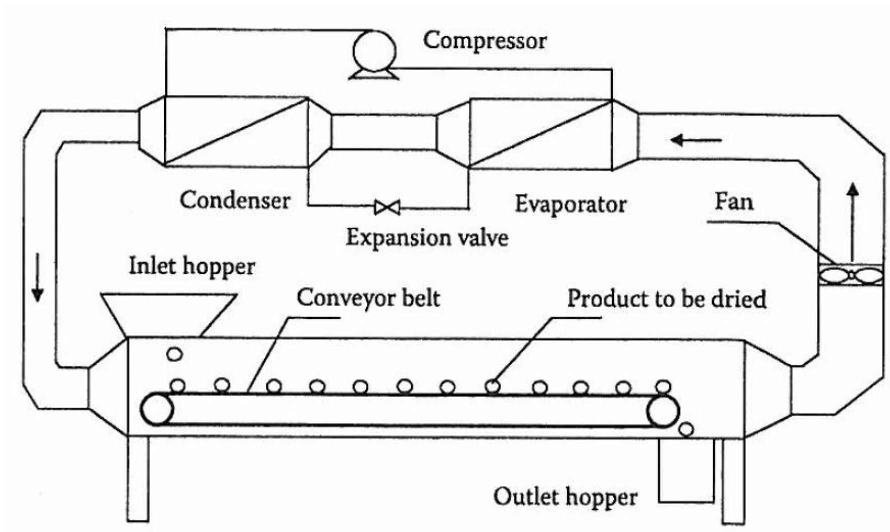

Figure 5.2 A continuous mode heat pump dryer.

CHAPTER 6

ENERGY MODEL

6 ENERGY MODEL

The study of this Master's Thesis is focused on obtaining a simulation model on the Engineering Equation Solver (EES) software to implement a combined air drying system, assisted by a heat pump. As it has been stated earlier, this way sensible and latent heat can be recovered from the exhausted air, increasing then the drying system efficiency, which implies energy savings.

The study product to which the drying system is applied is codfish. The cod has been previously treated with a salting process, in which the cod has been drown in salt for about three weeks, decreasing its water content from approximately 80% of initial water content to 55%-60% of moisture, as it has been already indicated in the paragraph 3.2.3 of this very Master's Thesis. The latter value of moisture content is the one with which the drying of the fish starts. For energy calculations, the initial value of moisture content for the drying process is selected as 55%. It has also been stated earlier in that same paragraph, that it is considered to have reached the desired dried fish when the total water content has reached a minimum value of 43-47%, so in this work it will be used an average value of 45% for the desired final water content.

It is important to maintain equilibrium between the water activity (a_w) in the salted fish and the relative humidity (RH) in the atmosphere air where the fish is stored. When the RH is higher than a value of a_w of 0.76, the salted fillets absorb water and gain weight, whereas the opposite is observed when the relative humidity is lower than a_w. [18]. So it is safe to consider that the equilibrium occurs when ERH (equilibrium relative humidity) is equal 76%, so it will be the value taken for the water activity in this work.

Strømmen's work "Tørking av klippfisk" ("Drying of clipfish") [19] is used to model the drying simulation. In his work, he gives theorical background and experimental data and parameters regarding the drying process of clipfish, which have been used in the modeling of this thesis.

At a given water content, by increasing temperature and decreasing relative humidity, the drying time decreases. There is a limit in the higher temperature to be used since high temperatures can result in “burning” the fish, an unwanted quality defect that would spoil the fish. According to Strømmen, the upper limit temperature for codfish is about 27°C, so a lower temperature is selected for the drying process, which will be 26°C. As for the relative humidity, to achieve a minimum water content, relative humidity has to get lower, but it shouldn’t be lower than 30% so as to avoid a hard dehydrated dry zone. The resulting drying process takes up 3 to 5 days to complete the dehydration and desired quality.

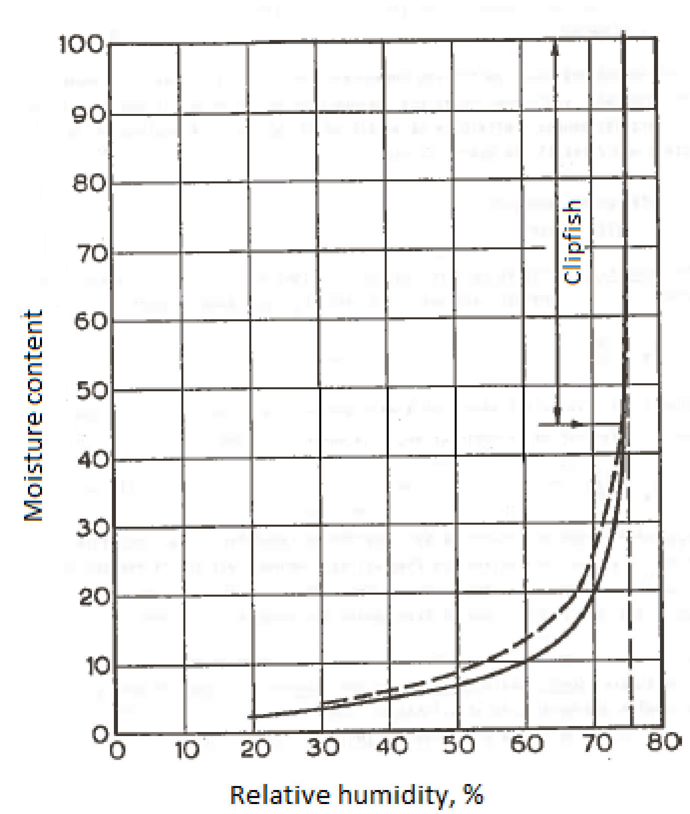

Figure 6.1. Sorption isotherms for clipfish.

In this work, the principles of the model of Strømmen are maintained, but the nomenclature is changed to facilitate the understanding. The process applies mass transfer and heat transfer equation for both phases of the drying process that occur, the transfer of heat and moisture from the surface to the hot air, as well as the transfer from the internal layers of the fish to its surface.

As it has been explained before, in the paragraph 3.2.3, the drying process consists of 2 different phases. The first one, while the fish has a moisture content higher than 50% and there are no dry layers in the fish, only the moisture on the surface is removed. Therefore, since the process starts with a 55% of water content in the fish, the first mass transfer equation needed is the one involving the transfer of moisture from the surface of the fish to the carrying hot air, express in Eq. 6.1.

$$\dot{m}_{water\ surface\ to\ air} = \sigma * A * (X_s - X_a) = \frac{\beta * A}{R_d * T} * (P_{w,s} - P_{w,a}) \quad \textit{Eq. 6.1}$$

Where the subscripts “s” and “a” refer to the surface of the fish and the air, respectively. The other parameters are defined as follows:

- $\dot{m}_{water\ surface\ to\ air}$: mass flow of moisture transferred [kg/s]
- σ : mass transfer coefficient from surface to air [$kg/m^2 \cdot s$]
- A : surface of the fish [m^2]
- X_s : absolute moisture content on the surface [$kg_{H2O}/kg_{dry\ air}$]
- X_a : absolute moisture content in the dry air [$kg_{H2O}/kg_{dry\ air}$]
- β : mass transfer coefficient from surface to air [m/s]
- R_d : gas constant for water vapour [J/kg·K]
- T : air temperature [K]
- $P_{w,s}$: vapour pressure on the surface [Pa]
- $P_{w,a}$: vapour pressure in the dry air [Pa]

When the water content decreases under 50%, dry layers begin to form, and the moisture transfer within the solid must be taken into account. Consequently, an additional second mass transfer equation is neccesary, involving the transfer of moisture from the internal layers of the fish to its surface, express in Eq. 6.2.

$$\dot{m}_{water\ core\ to\ surface} = \frac{A * D}{R_w * T_a * \mu * s} * \left(P_{w,c} - P_{w,s}\right) \qquad \textit{Eq. 6.2}$$

This new "c" subscript refers to the core of the fish, and as for the new parameters, they are defined as:

- *D* : diffusion coefficient of water [m^2/s]
- μ : diffusion of the dry layer in relation to the air [*adimentional*]
- *s* : thickness of the dry layer [m]
- $P_{w,c}$: vapour pressure in the core [Pa]

Elmiinating $P_{w,s}$, which appears in both equations, a global mass transfer equation is obtained as it follows in Eq. 6.3, so that calculations for the second phase of the process are easier to carry out:

$$\dot{m}_{water} = \frac{1}{R_w * T} * \frac{A}{\left(\frac{1}{\beta} + \frac{\mu * s}{D}\right)} * \left(P_{w,c} - P_{w,a}\right) \qquad \textit{Eq. 6.3}$$

After the mass transfer equations are stated, the heat transfer equations need to be defined. The same way the mass transfer equations were determined for each one of the phases of the drying process, heat transfer equations need to be defined in both phases.

The heat transfer equation for the first phase, when only evaporation of the surface water occurs, is defined in the following Eq. 6.4:

$$\dot{Q}_{air\ to\ surface} = \alpha * A * (T_a - T_s) \qquad \textit{Eq. 6.4}$$

For the second phase, a heat transfer equation involving the heat transfer between the internal layers of the fish must be defined (Eq. 6.5):

$$\dot{Q}_{surface\ to\ core} = \frac{\lambda * A}{s} * (T_s - T_c) \qquad \textit{Eq. 6.5}$$

The parameters in the last two equations yet to be defined are the folowing:

- α : heat exchange coefficient [W/m²·K]
- λ : thermal conductivity of the dry layer [W/m·K]

A global heat transfer equation involving the two latter equations to obtain the heat transfer equation for the second phase is expressed in Eq. 6.6 when the surface temperature is omitted:

$$\dot{Q}_{air\ to\ core} = \frac{A}{\frac{1}{\alpha} + \frac{s}{\lambda}} * (T_a - T_c) \qquad \textit{Eq. 6.6}$$

The mass flow of water content in the fish is related to the heat transferred from the air to the fish, needed for the evaporation of the water, through the latent heat of vaporization [J/kg], designated as *r*, as it is shown in Eq. 6.7.

$$\dot{Q}_{air\ to\ core} = \dot{m}_{water} * r \qquad \textit{Eq. 6.7}$$

Where $Q_{air\ to\ core}$ designates the heat transfer [J] involved in the vaporization of the moisture of the fish.

Mass and heat transfer coefficients are connected in Lewis relationship (Eq. 6.8):

$$\sigma = \frac{\alpha}{C_p} \qquad \textit{Eq. 6.8}$$

Where C_p is the specific heat capacity of the air [J/kg·K].

By applying Eq. 6.7 to the transfer between the air and the surface of the fish, we can relate mass and heat transfer between air and surface, resulting in Eq. 6.9:

$$\dot{Q}_{air\ to\ surface} = \dot{m}_{water\ surface\ to\ air} * r \qquad \textit{Eq. 6.9}$$

Applying Eq. 6.1 for mass transfer and Eq. 6.4 for heat transfer, with the Lewis relationship, Eq. 6.8, it is obtained Eq. 6.10:

$$\alpha * A * (T_a - T_s) = \frac{\alpha}{c_p} * A * (X_s - X_a) * r \qquad \text{Eq. 6.10}$$

Then, a simplified equation is obtained, Eq. 6.11, finding the equality of air enthalpies definitions:

$$c_p * T_a + r * X_a = c_p * T_s + r * X_s \qquad \text{Eq. 6.11}$$

This equation, Eq. 6.12, shows that at equilibrium, the enthalpy of the surface (h_s) is equal to the enthalpy of dry air (h_a).

$$h_a = h_s \qquad \text{Eq. 6.12}$$

In his work, Strømmen shows a schematic representation of the heat and mass exchange in both drying phases, along with a psychrometric chart of the humid air.

In the Figure 6.2, it is shown the representation of the first phase, involving the transfer of mass and heat between the surface of the fish and the dry air.

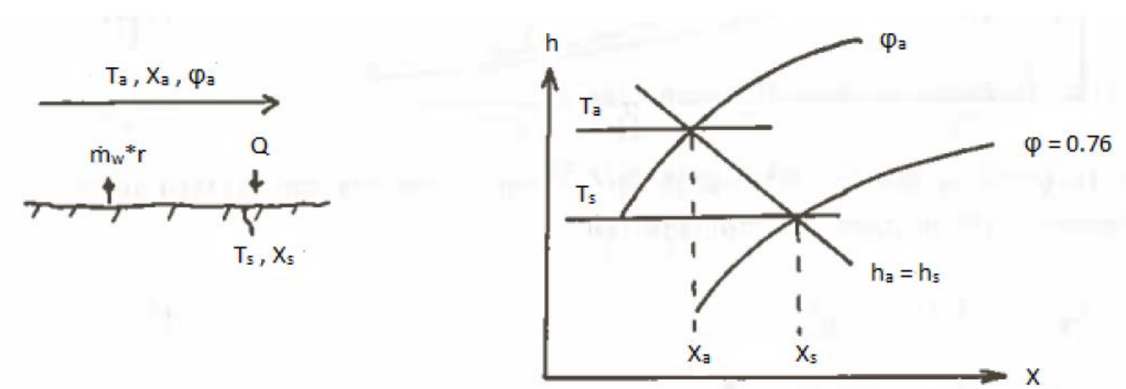

Figure 6.2. First drying phase, drying from the surface.

In the following Figure 6.3, the second drying phase is shown, in which both surface to dry air and core to surface mass and heat transfers are represented. It can be seen that the drying rate falls in the core to surface drying.

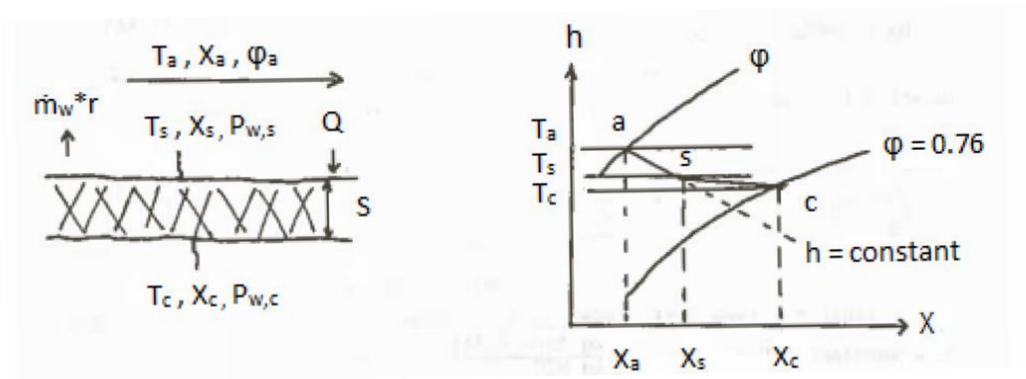

Figure 6.3. Second drying phase, drying from the core.

Using again heat and mass transfer relation shown in Eq. 6.9, and applying the Lewis relationship Eq. 6.8, but in this case applied to the core to surface transfer equations Eq. 6.2 (mass transfer) and Eq. 6.5 (heat transfer), the new obtained equation is shown in :

$$\frac{T_s - T_c}{p_{w,c} - p_{w,s}} = \frac{D * r}{R_w * T * \mu * \lambda}$$ *Eq. 6.13*

Assuming that the ideal gas law (Eq. 6.14) applies, it is possible to convert Eq. 6.13 into Eq. 6.15, and therefore obtaining the slope in the psychrometric chart.

$$p_w = \rho * X * R_w * T$$ *Eq. 6.14*

$$\frac{T_s - T_c}{X_c - X_s} = \frac{D * r * \rho}{\mu * \lambda} = \frac{K}{\mu * \lambda}$$ *Eq. 6.15*

Where a new constant is defined:

- K : constant equal to *(Dρr·)* [$W \cdot kg_{dry\ air}/m \cdot kg_{H2O}$]
- ρ : density of dry air [$kg_{dry\ air}/m^3$]

In order to resolve the equations of the modeling, parameters have to be determined.

First, Strømmen relates the vapor pressure with the air temperature and relative humidity with experimental data. The following relationship is obtained in Eq. 6.16.

$$P_{w,c} = a_w * 10^{\left(11.232 - \frac{2305.3}{T_c}\right)}$$ Eq. 6.16

Where all he parameters have been previously defined.

The next parameter to determine is the heat transfer coefficient correlation with the air speed. Strømmen uses the model from Grøber/Erk/Grigull applicable in a tunnel with L/D < 10 (ratio between the length of the tunnel and its diameter). This model (Eq. 6.17) relates the three adimentional numbers of Nussel, Reynolds and Prandtl.

$$Nu = 0.027 * \left(1 + \left({}^{D_H}/_{L}\right)^{2/3}\right) * Re^{0.8} * Pr^{0.3}$$ Eq. 6.17

Where the parameters in the equation are defined as follows:

- *Nu* : Nusselt number [adim.]
- *Re* : Reynolds number [adim.]
- *Pr* : Prandtl number [adim.]
- *L* : Length of the drying tunnel [m]
- D_H : Hydraulic diameter of the tunnel [m]

The adimentional numbers are defined in Eq. 6.18 (Nu), Eq. 6.19 (Re) and Eq. 6.20 (Pr).

$$Nu = \frac{\alpha * D_H}{\lambda_a}$$ Eq. 6.18

$$Re = \frac{w * D_H}{\nu}$$ Eq. 6.19

$$Pr = \frac{\mu_a * C_{pa}}{\lambda_a}$$ *Eq. 6.20*

Where:

- λ_a : thermal conductivity of the air [W/m·K]
- w : air velocity inside the chamber [m/s]
- ν : kinematic viscosity of the air [m^2/s]
- μ_a : dynamic viscosity of the air [kg/m·s]
- C_{pa} : air heat capacity at constant pressure [J/kg·K]

Then the hydraulic diameter is to be defined in Eq. 6.21:

$$D_H = \frac{4 * S}{p_b} = \frac{4 * B * h}{2 * B} = 2 * h$$ *Eq. 6.21*

Where the parameters of the chamber are:

- S : cross sectional area for the air current [m^2]
- p_b : wetted perimeter [m]
- B : width of the single layer [m]
- h : height between one layer and another [m]

It is then possible to obtain an equation relating the heat transfer coefficient to the air velocity, as shown in Eq. 6.22.

$$\alpha = C * w^{0,8}$$ *Eq. 6.22*

Another parameter to define is the specific air enthalpy as a measure of the energy content of air, as a function of the temperature and specific humidity of air, Eq. 6.23.

$$h = C_{p,a} * T_a + X_a * \left(r + C_{p,v} * T_a\right) \quad \textit{Eq. 6.23}$$

Where:

- $C_{p,v}$: vapour heat capacity at constant pressure [J/kg·K]

Although heat capacities of air and vapor are not constant variables, since they change in the range of temperatures, for this model it is safe to make the assumption that they remain constant, since that would lead to minimal error in the calculation.

Giving then the following relationship between absolute humidity and water vapor pressure, in Eq. 6.24.

$$X_a = 0{,}622 * \frac{P_{w,a}}{P - P_{w,a}} \quad \textit{Eq. 6.24}$$

Finally, other defined parameter is the mass transfer coefficient related to the heat transfer, as it can be seen in Eq. 6.25:

$$\beta = \frac{\alpha}{\rho_a * C_{p,a}} \quad \textit{Eq. 6.25}$$

Data from the model made by Strømmen as well as measured data from the Master's thesis of Luca Zanfrisco [20], from a fish dryer.

- Water activity: $a_w = 0.76$
- Temperature of dry air: T_a= 26°C = 299.16K
- Atmospheric pressure: P_{atm}= 101325Pa
- Relative humidity: 30%
- Constant air velocity: w= 2.0 m/s
- Gas constant for steam: R_d = 462 J/kg·K
- Diffusion coefficient for water vapor in air: D= 2.61×10^{-5} m^2/s
- Heat conductivity of the dry layer: 0.1 W/m·K
- Total external surface of the fish : A= 0.126 m^2
- Latent heat of vaporization: r= 2500 kJ/kg
- Heat capacity: C_{pv} = 1860 J/kg·K
- Mass of the fish: m = 1 kg
- Measures of the chamber:
  - L = 0.55 m
  - b = 0.34 m
  - a = 0.10 m

CHAPTER 7

RESULTS

7 RESULTS

The study of the simulation has consisted in two different parts, as it has been earlier explained. According to the two phases that comprises the process of drying, the simulation has been done separately for both phases.

In the first phase, the process has been calculated according to the data and equations indicated in the model. The first phase consists on the drying fish to achieve a water content of 50%, from its initial 55% of water content. After it is achieved, the second phase of the drying process takes part. There, the drying aims to achieve a water content of the fish of 45%.

As it has been explained in the model, the optimal conditions of the parameters of the chamber are an initial temperature of the hot air of 26 C and a relative humidity or RH of 30%. The optimal hot air velocity is 2.0 m/s. The fish to be dried are considered to have been treated before in a salting process, and that is why their initial moisture content value is such low as 55%.

The simulation implemented in the software EES has been used to evaluate the drying time and parameters of the process with the given conditions, comparing it to when the process conditions changed.

The first study is focused on the results of the optimal conditions of the process to evaluate the procedure and as a measure with which compare the other conditions. Therefore, the first results obtained are for fish of 1kg of mass and with the conditions of the chamber of a hot air temperature of 26 C, relative humidity of air of 30% and 2m/s as the air velocity. The drying time obtained for the process is shown in Figure 7.1 the below.

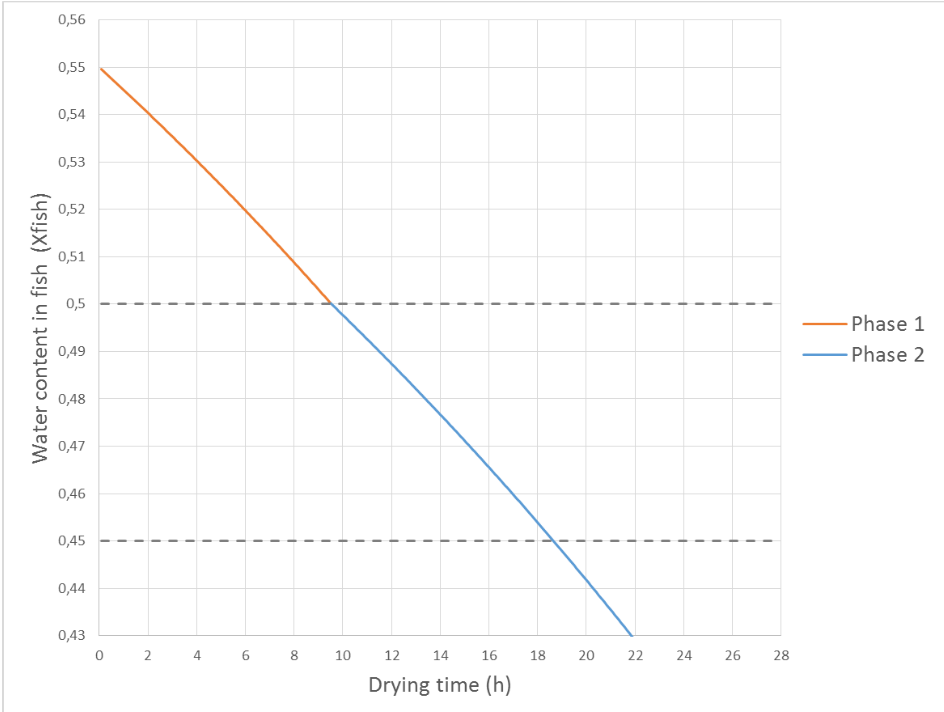

Figure 7.1 Drying time of clipfish at given conditions.

From the figure above, there are shown in different colors the two phases of the drying process in which the fish take part. As it has been explain, the fish first dries until it gets to a moisture content of 50% in the first phase of the process, where only surface drying takes part. Then in the second phase, it dries until a moisture content of 45%, where apart from surface drying, there is also a mass and heat transfer of moisture from the inner layers of the fish to its surface. It can be seen in the figure that with the given conditions, fish get to the desired moisture content of phase 1, 50% of water content, after more than 9 hours, and finally reached the final product moisture content of 45% after nearly 19 hours of process, which means another 9 hours in the second phase.

The results of the data result of the drying time are shown in the table below, Table 7.1.

T=26C, RH=30%, w=2m/s, m=1kg	X = 50%	X = 45%
Drying time (h)	9,50	18,67

Table 7.1. Results of drying time of clipfish at given conditions.

With this moisture content, the evolution of the drying rate is relatively constant. At lower moisture content, lower than the aimed one, the drying rate decreases a lot since there is an increasingly resistance hindering the movement of the moisture from the inner layers of the fish to the surface. The "increasingly" aspect of the behavior at low water content values is not taken into account in this simulation, but the drying process of the codfish is aimed to reach a water content of 45%, so this does not affect the purpose of the study of the drying system.

It has been stated that a temperature of 26 C is the optimal for the process, since the higher the temperature is, the faster the drying process will be, but there is the 27 C of temperature limit due to quality requirements. This work has implement the study with lower temperatures to evaluate the results of drying time. Heat pump driers should operate with temperatures no lower than about 20 C and up to 65 C, so the range is low given that the higher temperature is 26 C. The temperatures used in the study are 16 C, the lowest one considered, and an intermediate temperature of 21 C.

The other parameters of the simulation have been maintained. The results of the simulation with the different temperatures used are shown in the Figure 7.2 below,

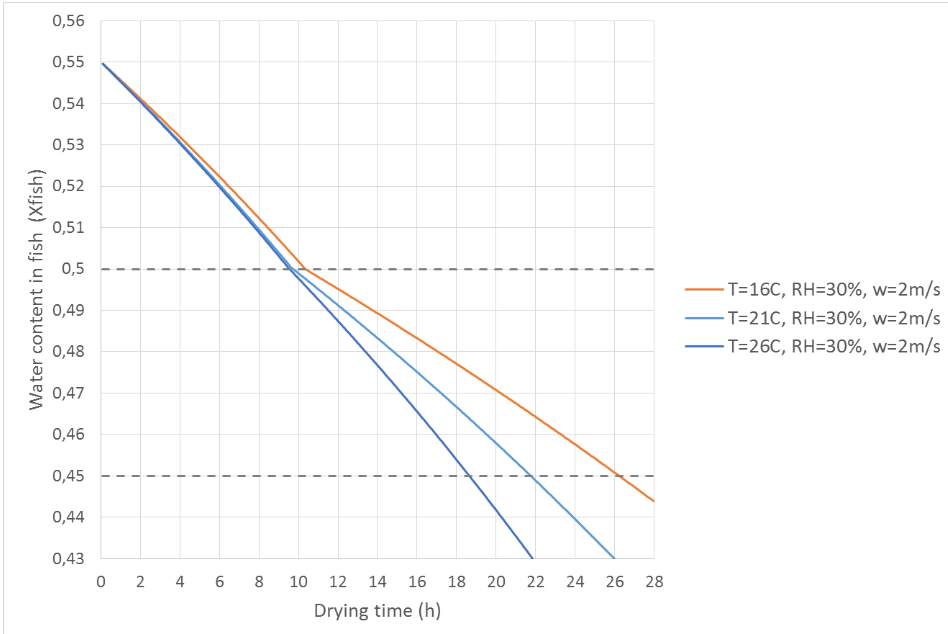

Figure 7.2 Drying time of clipfish at compared temperatures.

The results are consistent with the thought behavior, the lower the temperature is, the lower the heat exchange will be and therefore the lower the drying rate. It can be seen in the figure above that during the first phase of the process the differences on the drying rates are not as visible as in the second phase of the drying process.

In the first phase of the process, the heat transfer involved is only that of the surface of the fish to the hot air. When the air temperature changes decreasing, the direct heat transfer between surface and air decreases in a relatively direct proportion. Nevertheless, in the second phase, it must be taken into account the resistance of the moisture movement. That is why the differences on the slope among the different temperatures and phases are more noticeable and it decreases increasingly with the different temperatures.

The different values of the results obtained for these temperatures are shown in Table 7.2.

RH=30%, w=2m/s, m=1kg	X = 50%	X = 45%
Drying time (h)		
T = 26 C	9,50	18,67
T = 21 C	9,67	21,75
T = 16 C	10,33	26,25

Table 7.2 Results of drying time of clipfish at compared temperatures

Another of the parameters of the simulation which should be discussed is the relative humidity of the hot air. Heat pump drying systems should operate in a range of relative humidity of about 30% to 100%. In this process the lowest relative humidity of 30% is taken since a higher relative humidity means that the air-water mixture is more humid and therefore the heat transfer will be lower.

To verify that this low relative humidity of the air is optimal for the process a comparison between the low relative humidity and a higher one has been made with the simulation. The lower relativity selected has been 40% of RH. The graph comparing both results is shown in Figure 7.3.

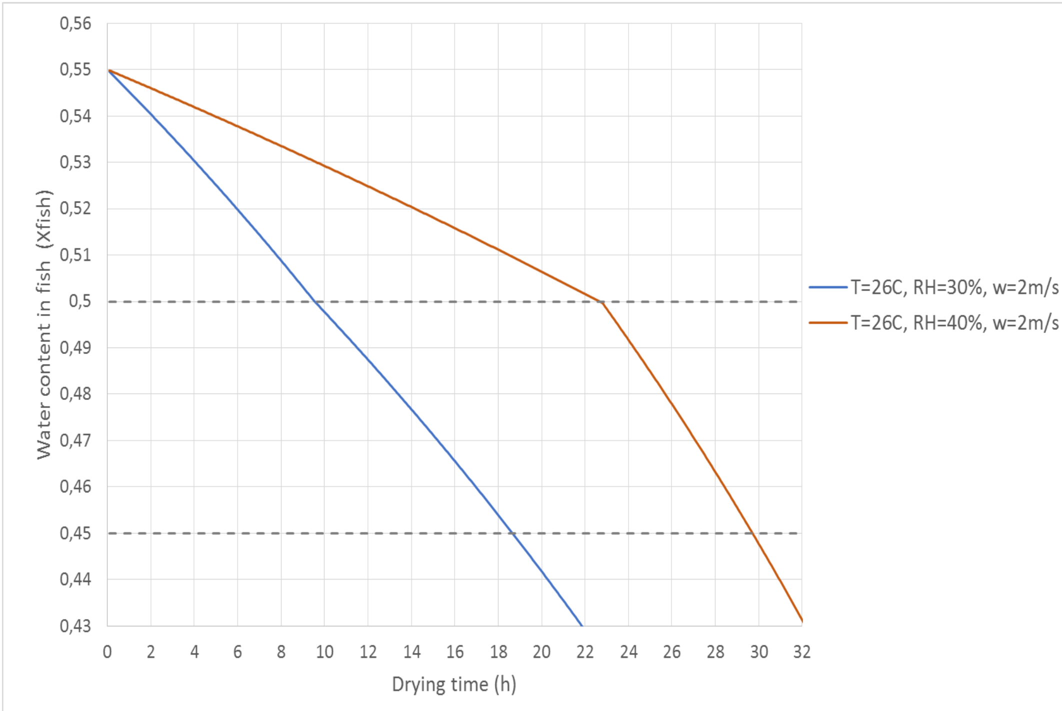

Figure 7.3 Drying time of clipfish at compared RH with temperature of 26C.

For a high relative humidity, a high temperature implies a diminution of the heat transfer and therefore a decrease on the drying rate. However, since the physical mechanisms change in the second phase of the progress, the drying rate evolves differently in this phase, affecting in an opposite direction. This evolution of the drying rate is noticeable in the figure above. The proportionality between the relative humidity and the temperature is more noticeable in the figure below, Figure 7.4, where the high RH used in the study has been used in a simulation with the other temperatures used earlier.

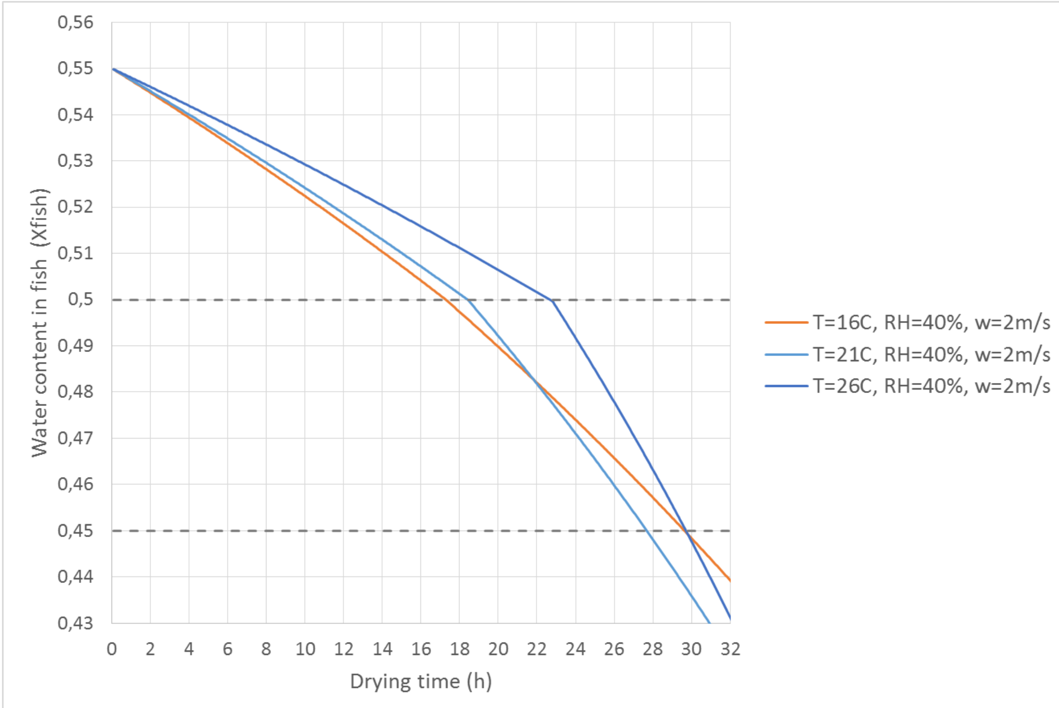

Figure 7.4 Drying time of clipfish at compared temperatures with RH of 40%

The behavior at high relative humidity changes completely as compared to low temperatures. As it can be deduced from the figure above, higher relative humidity benefits lower temperature in the first stage of the drying, but in the second phase of the process, the higher the temperature, the better for the drying rate.

The Table 7.3 below shows the results obtained by the comparison of the high relative humidity with the different temperatures.

RH=40%, w=2m/s, m=1kg	X = 50%	X = 45%
Drying time (h)		
T = 26 C	22,67	29,67
T = 21 C	18,42	27,67
T = 16 C	17,25	29,60

Table 7.3 Results of drying time of clipfish at compared temperatures with RH 40%

The results in the table above, compared to the results shown in Table 7.2, are an indicator that increasing the relative humidity of the air is not a suitable election in order to improve the results of the drying system, since the drying time increases notably as the relative humidity increases. With a 30% of relative humidity, the drying times of the entire process in the three cases are lower than 27 h; while with a 40% of relative humidity, the drying times are all higher than 27 h.

The next parameter to study is the velocity of the hot air flow in the chamber. The velocity used in the work for optimal results is an air velocity (w) of 2 m/s. As it has been seen before, the resistance to the drying in the second phase makes the first phase be more sensitive to the variations of the parameters. The velocities selected to be compared to the given velocity of 2 m/s are a lower one, 1 m/s, and a higher one, 3 m/s.

Low air velocities are not good for the heat exchange, since low velocities near a steady mode do not favor the exchange along the tunnel and thus the drying time is very large for low velocities. For velocities higher than 2 m/s the results are much better, but a consideration must be made, being that with a higher velocity the drying time decreases and therefore the production increases, but that also means an increased fan capacity.

The following Figure 7.5 shows the results of the simulations made for the optimal temperature and RH of 26C and 30% respectively, with the three air velocity cases.

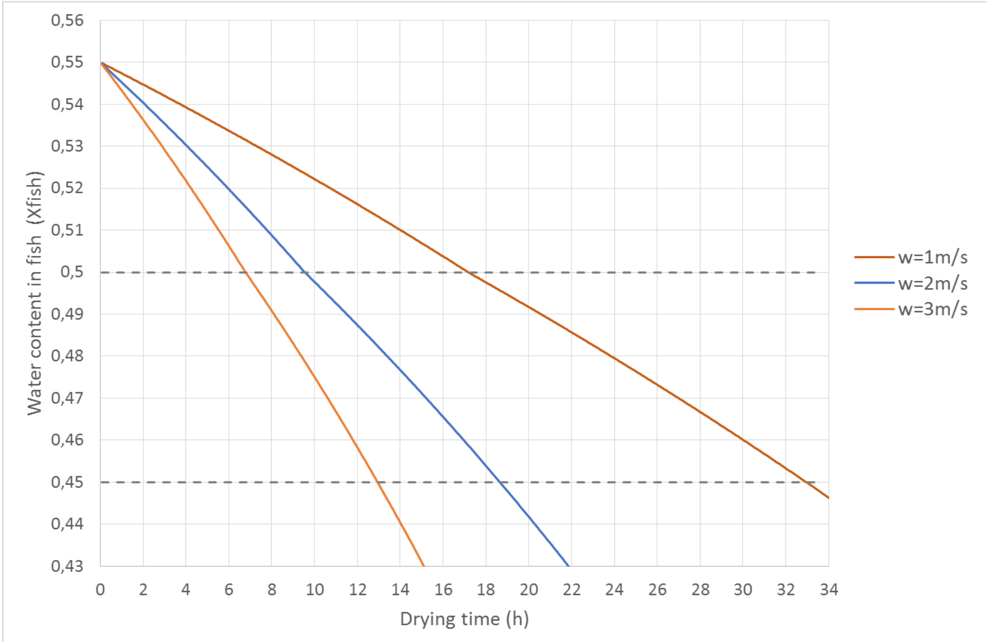

Figure 7.5 Drying time of clipfish at compared air velocity with temperature of 26C.

As expected, the lowest air velocity increases by far the drying time. Only by increasing the air velocity to 2 m/s, the drying time improves by several hours, which is an important fact for the production of the drier. Higher velocities than 2 m/s, as it can be seen with the results of the velocity of 3 m/s, increase the drying rate, but it is not a such notably increase as the one observed when the velocity increases from 1 m/s to 2 m/s. As said before, since the drying rate increases as the velocity increases but this increase may not be as relevant, economical aspects of the increase production versus the fan capacity of the heat pump must be taken into account.

The data results of the simulation are shown in the following table, Table 7.4,to appreciate the wide differences in the drying times.

T=26C, RH=30%, m=1kg	X = 50%	X = 45%
Drying time (h)		
w = 1 m/s	17,17	33,00
w = 2 m/s	9,50	18,67
w = 3 m/s	6,75	12,92

Table 7.4 Results of drying time of clipfish at compared velocities

As it was shown in the graph, and can be stated by looking at the table above, the differences in the results among velocities is remarkable. With an air velocity of 3 m/s, fish reach the desired water content hours before fish with air velocity of 1 m/s have even reached the desired moisture content to finish the first phase.

The cases with the different air velocities have been simulated with the different temperatures as well. That is so it can be studied whether some velocities may be more suitable with a different range of temperatures.

The results for the simulation made for the air velocity of 1 m/s are shown in the following table, Table 7.5, and in the figure below, Figure 7.6.

RH=30%, w=1m/s, m=1kg	X = 50%	X = 45%
Drying time (h)		
T = 26 C	17,17	33,00
T = 21 C	17,42	-
T = 16 C	18,58	-

Table 7.5 Results of drying time of clipfish at compared temperatures with w 1m/s

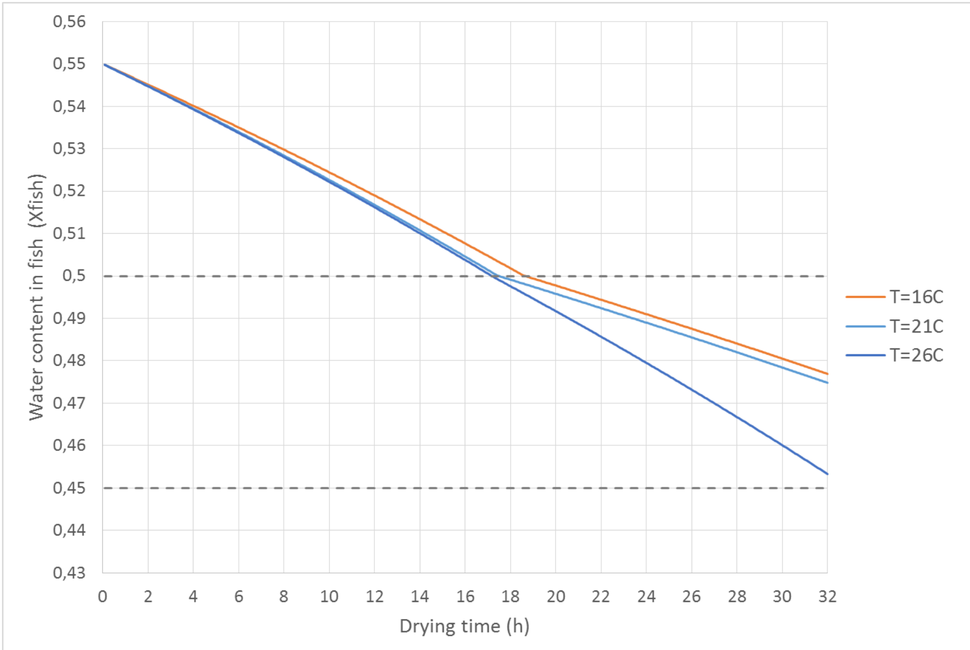

Figure 7.6 Drying time of clipfish at compared temperatures with velocity of 1m/s

The results show that in the first phase of the drying process there is little difference among the different temperatures, especially at high temperatures. Nevertheless, in the second stage of the process, the slopes start to differs, and now the lower temperatures tend to a lower behavior, which is decreasing rapidly the drying rate of the process. The highest temperature, the optimal 26 C, does not show that pronounce decrease of the drying rate as the lowest temperatures.

Overall, it is observed that low temperatures increase drying time, and this tendency increases notably when the velocity of the hot air decreases.

For the other case for the air velocity of 3 m/s, the results are shown in the table below, Table 7.6, and in the figure that follows, Figure 7.7.

RH=30%, w=3m/s, m=1kg	X = 50%	X = 45%
Drying time (h)		
T = 26 C	6,75	12,92
T = 21 C	6,92	18,42
T = 16 C	7,33	18,92

Table 7.6 Results of drying time of clipfish at compared temperatures with w 3m/s

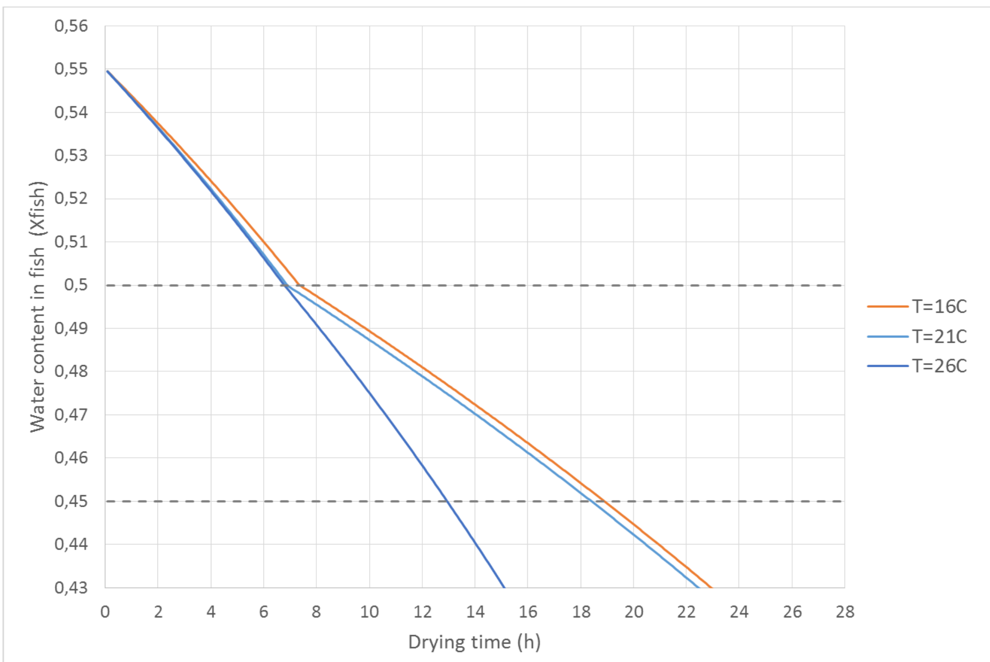

Figure 7.7 Drying time of clipfish at compared temperatures with velocity of 3m/s

Comparing this figure with that of the results for velocity of 1 m/s, it can be observed that the appearance of the slopes are similar. The drying times in this case are much lower than the previous case, increasing the drying rate more than twice as the other ones. However, the behavior is the same for both cases, as it was expected. In the first phase the drying times are rather similar and in the second phase the lower temperatures decrease their drying rates much notably than high temperatures.

However, it can be observed that the results may not differ a lot from the results at optimal conditions (Figure 7.2) with air velocity of 2 m/s. The results of the velocity of 3 m/s for the medium temperature of 21 C is quite similar to the optimal conditions results, and they do not differ many hours in the case of the optimal temperature of 26C either. Yet, the lowest temperature experiments the greater improvement of them all.

The last parameter considered to carry out the simulation is the mass of the fish. The considered mass of the fish to perform all the simulations has been 1 kg. For this simulation, a larger fish is considered to observe whether the process evolve in a proportional way. The mass considered in this simulation is a 2kg fish.

The simulation is made at the optimal conditions of the simulation, 26 C of temperature, RH 30% and an air velocity of 2 m/s. With such parameters, the results of the simulation are shown in the following Table 7.7 and Figure 7.8.

T=26C, RH=30%, w=2m/s	**X = 50%**	**X = 45%**
Drying time (h)		
m = 1 kg	9,50	18,67
m = 2 kg	19,08	42,17

Table 7.7 Results of drying time of clipfish at compared masses

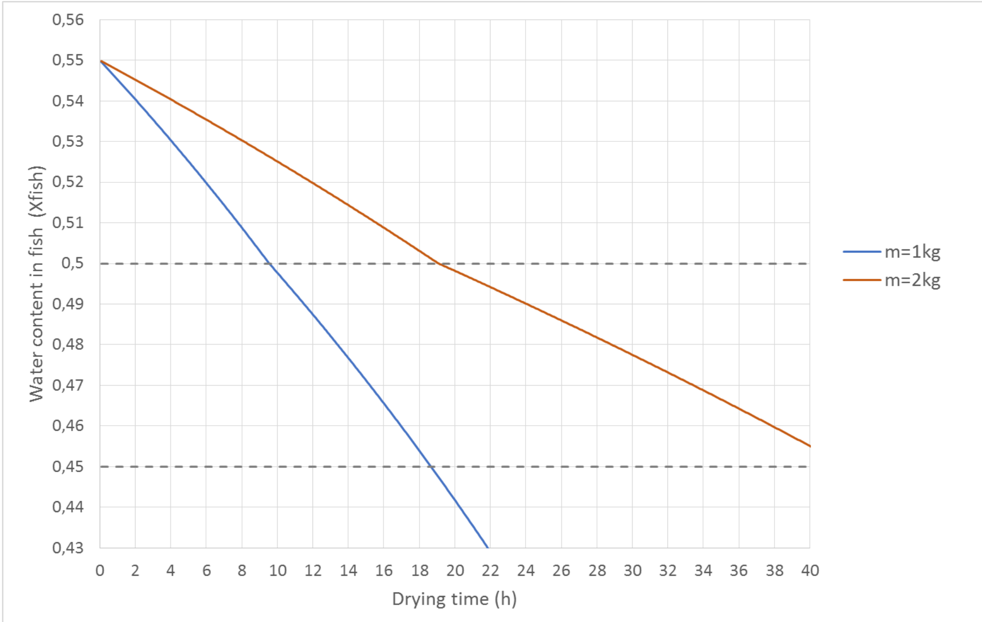

Figure 7.8 Drying time of clipfish at compared fish mass with temperature of 26C

As it can be noted in the figure and with the data results of the simulation in the table above, during the first phase, the drying time of the larger mass increases twice as much the 1kg mass, in a proportional way to the increase of the masses. In the second phase, it can be observed that the larger mass increases a little bit more than twice. Nevertheless, this increase is not very pronounced, and it may be due to the fact that the internal resistance of movement of the moisture may be bigger for bigger fish.

Following this case, another simulation has been done to compare this case of increased mass with the other studied temperatures. The other parameters maintain their optimal values.

The results of the simulation with the increased mass are shown in the following temperatures. They are plotted in Figure 7.9, with the results shown in Figure 7.2, so that they can be easily compared to the results for fish with a 1 kg mass.

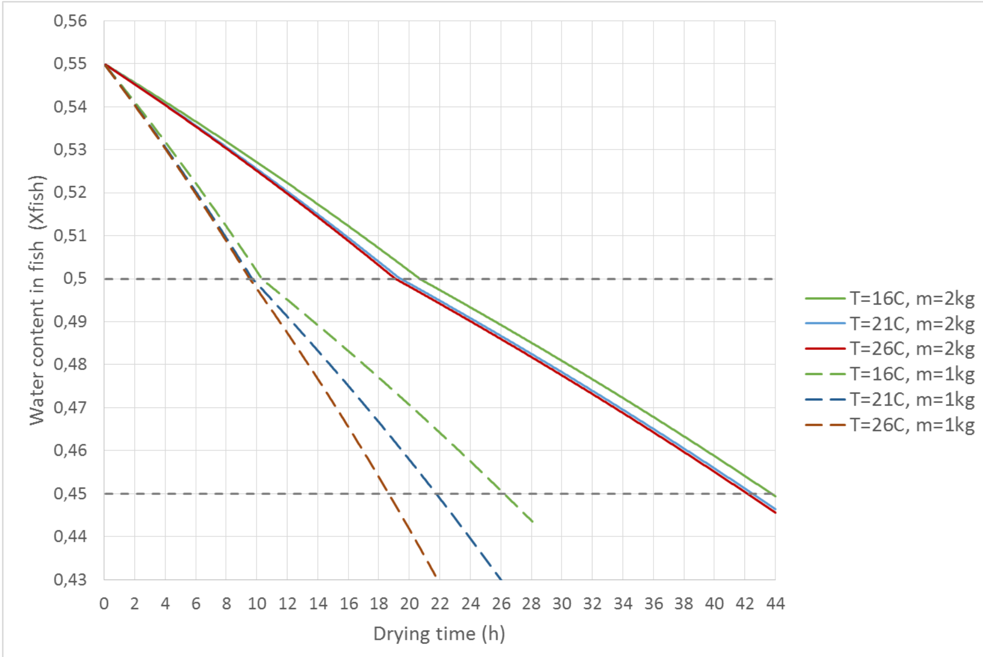

Figure 7.9 Drying time of clipfish at compared temperatures with mass of 2kg

As it can be observed from the comparison, at a mass of 1 kg there is big difference in the drying rates during the second phase, being relevant the use of higher temperatures to achieve a more productive drying rate. Nevertheless, when the mass is increased, it is noted that, although the drying time increases twice as much, the difference among drying rates is not as big as in the previous case. That means that there is not much difference among the drying times of the different temperature cases when the mass is increased. In order to be able to notice this difference in drying times, the following Table 7.8 shows the data results of drying times of the simulation with the large mass.

RH=30%, w=2m/s, m=2kg	X = 50%	X = 45%	RH=30%, w=2m/s, m=1kg	X = 50%	X = 45%
Drying time (h)			**Drying time (h)**		
T = 26 C	19,08	42,17	**T = 26 C**	9,50	18,67
T = 21 C	19,33	42,50	**T = 21 C**	9,67	21,75
T = 16 C	20,67	43,75	**T = 16 C**	10,33	26,25

Table 7.8 Results of drying time of clipfish at compared temperatures with m 2kg and 1kg

In the previous table, the results from this case of 2 kg mass fish and the previous one of 1 kg are shown to compare the drying times. Comparing the results obtained in both cases after the first phase, it can be observed that the drying times are proportional to the mass increase; when the mass is increased to double it, the drying times increase double as well. However, it can be noted that for the second phase, the increase is not that proportional. The difference in the results is not that relevant. That may involve that for larger fish it may not be worth it to increase the temperature to its higher value, since it increases energy requirements and the productivity does not increase in an outstanding rate.

As it has been explained before, the data of the simulation have been extracted from the experimental work from Strømmen. That way, to verify the correct operation of the simulation, the results obtained with the simulation can be compared to the results obtained in the experiments of Strømmen.

First of all, the results for the optimal selected parameters will be compared. As it has been shown before, the drying time results for the simulation in this work were in Table 7.1, shown again in the following table:

T=26C, RH=30%, w=2m/s, m=1kg	X = 50%	X = 45%
Drying time (h)	9,50	18,67

Table 7.1 Results of drying time of clipfish at given conditions

Strømmen, in his work, on page 45, shows the results experimentally obtained for the initial conditions of 26 C of temperature, 30% RH and velocity of 2 m/s, the ones that have been selected as optimal. The initial water content of the fish is not the same though. In this work, the initial water content is taken as 55%, while the measures of the fish in his work give initial water contents of 52.3%, 53.3% and a higher one of 59.5%.

The behavior expected for product with water content of 55% like in this case, an approximate interpolation from the experimental data is needed.

The figure showing the Strømmen results is shown below, Figure 7.10. From there, it can be observed that with an initial water content as high as 59.5% the drying time until it get to the desired final water content of 45% is about 32 hours. However, for lower initial water contents such as 52.3% and 53.3%, closer to the water content of 55% used in this work, the drying times are about 12 and 17 hours respectively. Those values are close to the obtained value for the optimal conditions in the simulation.

With this comparison it can be assumed that the simulation for the optimal condition works correctly.

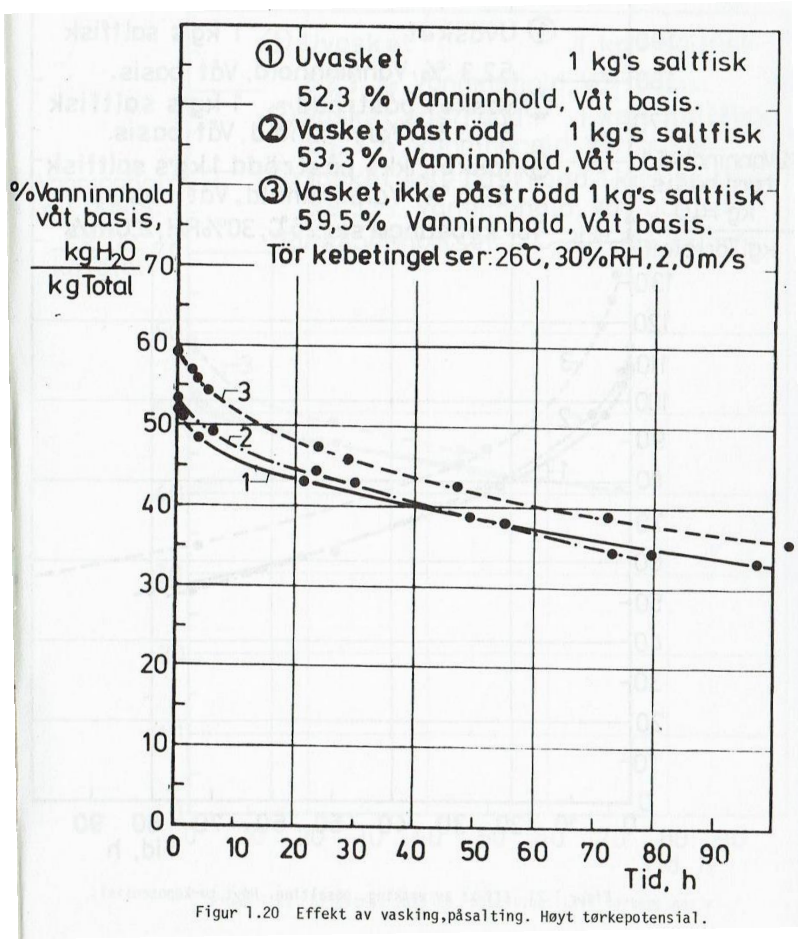

Figure 7.10 Strømmen results (1).

For the next comparison between the Strømmen experiments and the simulation of this paper, the simulations of the changes in temperature are compared. In his work, on page 47, he performs the experiments with the original conditions, but at a lower temperature of 17 C. This way, the change in temperature in the simulations of this Master's Thesis can be compared by using the data from the simulation at optimal conditions with temperature of 16 C.

An extract from Table 7.2, were the drying results for temperature of 16 C can be observed as follows:

T=16C, RH=30%, w=2m/s, m=1kg	X = 50%	X = 45%
Drying time (h)	10,33	26,25

Table 7.12 Results of drying time of clipfish at compared temperatures

The results from the experiment are shown in the following figure, Figure 7.11 .

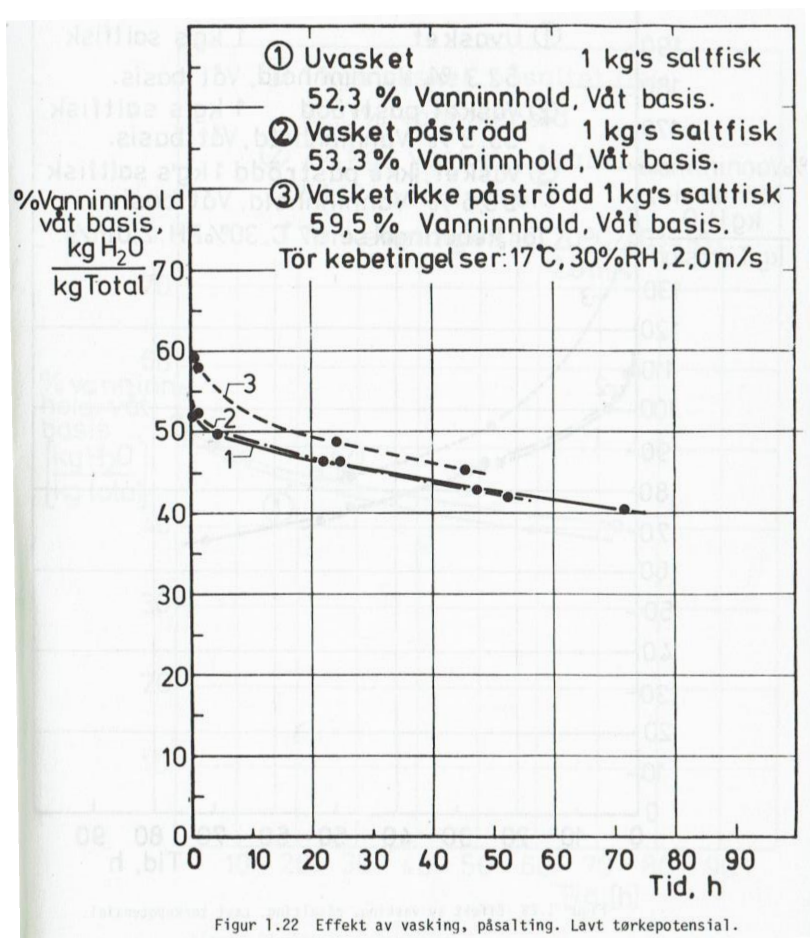

Figure 7.11 Strømmen results (2).

The comparison shows that the results from the simulation and the experiments are not as accurate as in the previous case. In this case, with the same initial water content of 52.3%, 53.3% and 59.5%, the drying times are larger than the calculated in the simulation model. With the water content of 59.5% the difference is great, with a drying time of more than 45 hours for the experiment. With the lower water contents both drying times are about 30 hours, a result a little bit larger than the one obtained in the simulation, which is 26.25 hours for an initial water content of 55%. The biggest difference is caused by the second phase of the process. The drying rate decreases a lot in the experiments, while it does not decrease as much in the simulation. This can be caused because the internal resistance of the fish to the movement of the moisture from the inner layer to the surface is very marked in the experimental cases.

The last comparison between the experimental work of Strømmen and the simulation model of this work takes into account a simulation con a combination of two changed parameters. Strømmen carries out an experiment with fish at 20 C of temperature and 40% RH. That way, the simulation with a changed temperature of 21 C and a changed relative humidity of 40% can be compared and verified.

In the following table is represented the results for the 21 C of temperature from Table 7.3.

T=21C, RH=40%, w=2m/s, m=1kg	**X = 50%**	**X = 45%**
Drying time (h)	18,42	27,67

Table 7.3 Results of drying time of clipfish at compared temperatures with RH 40%

The results for the experiment of Strømmen, shown on the page 49 of his work, are shown in the extracted figure of the book, Figure 7.12.

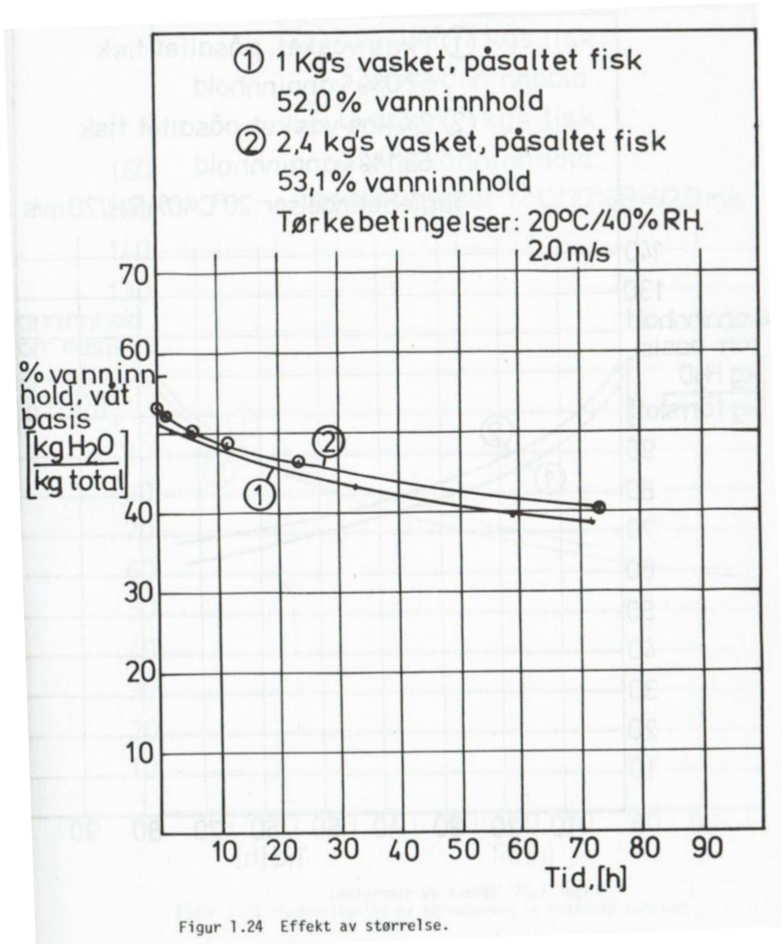

Figure 7.12 Strømmen results (3).

From the figure, it can only be taken into account the first water content of 52.0%, since the other one is related to larger fish.

The experimental result of drying time is about 24 hours. For the case contemplated in the simulation of this work, with an initial water content of 55%, the desired final water content of 45% is achieved in a drying time of 27.67 hours. The variation between the results is not really large, so it can be verified by the experiment that the simulation model works for the different configurations.

CHAPTER 8
ECONOMIC ASPECTS

8 ECONOMIC ASPECTS

An economic studio has to be held to check the economic viability corresponding to the installation of a heat pump system as energy supplement for the drying plant with hot air system. Has therefore been done a studio in which investment and operating costs of both methods are compared, obtaining an approximate value of total cost of both facilities. This way it can be compared and discerned based on economic performance, which is the best method to implement the drying process.

The studio has been made approximately. Since to do so, it has not been taken into account data and costs of labor, feedstock and other additional expenses of the process.

The conditions that have been taken for the designed process conditions have been based on a temperature of dry air inside the tunnel 26 C as already indicated in previous sections. In Figure 8.1, obtained from Strømmen's Book, pg. 138, the relationship between temperature and dry air distribution trolleys within the drying tunnel is observed. Data taken as trolleys are 4 units in width of the tunnel and 16 in length. Thus, a production of 10.9 tons of fish per day is obtained.

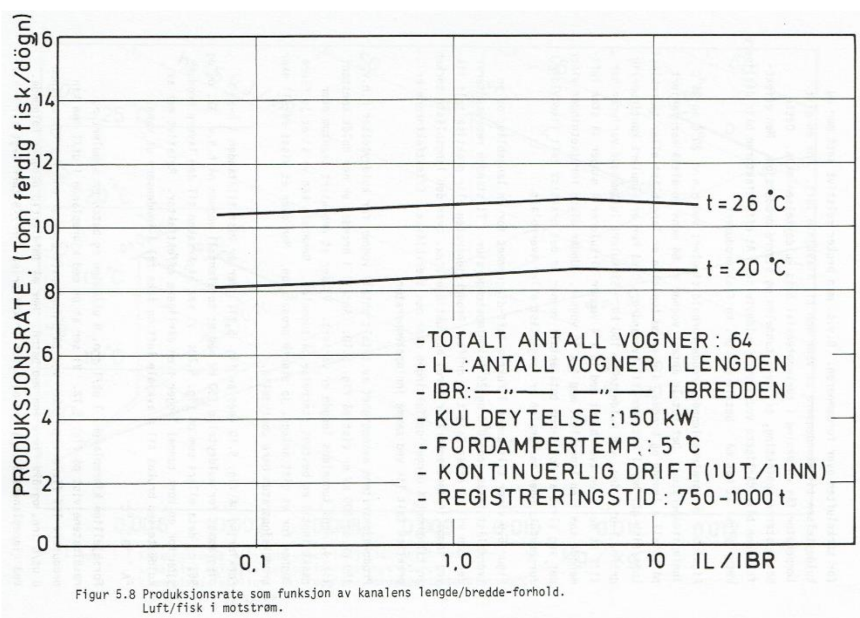

Figure 8.1 Production rate vs. trolley distribution inside the tunnel.

Then, by reference to Figure 8.2, obtained from the page 152 of the same paper, through data dry air temperature of 26 C and just obtained production of 10.9 tons fish per day, a temperature of surface of the evaporator of 5 C is obtained.

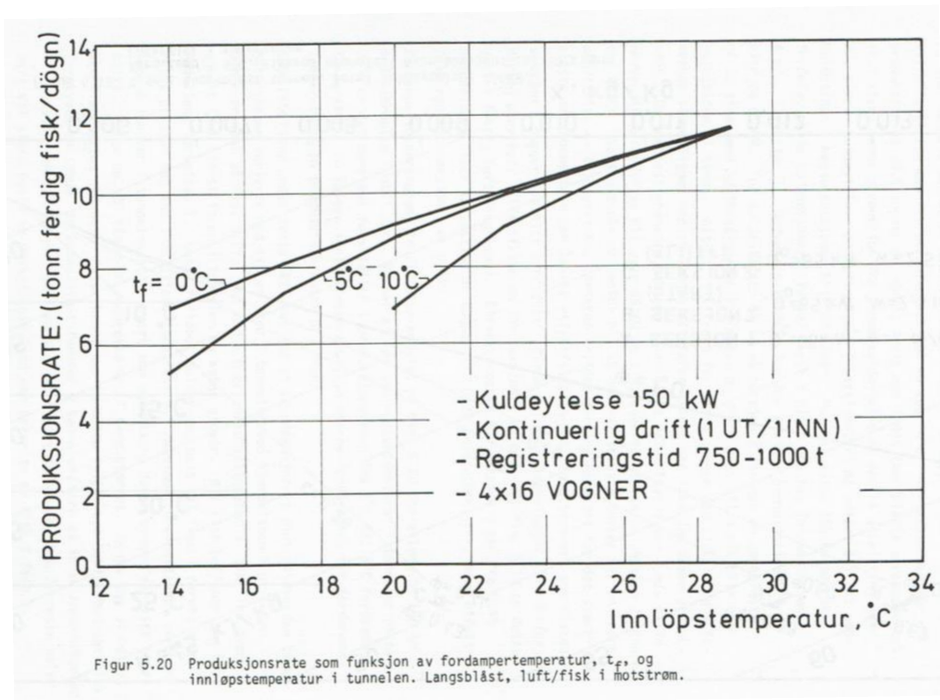

Figure 8.2 Production rate vs. temperature of dry air. (Evaporator temperature)

From Strømmen's work, the Figure 8.3 is also obtained from page 135. In this figure, the cooling performance of the drying plant is obtained. For dry air temperature of 26 C and the indicated production of 10.9 tons fish / day, Q is obtained as 150 kW.

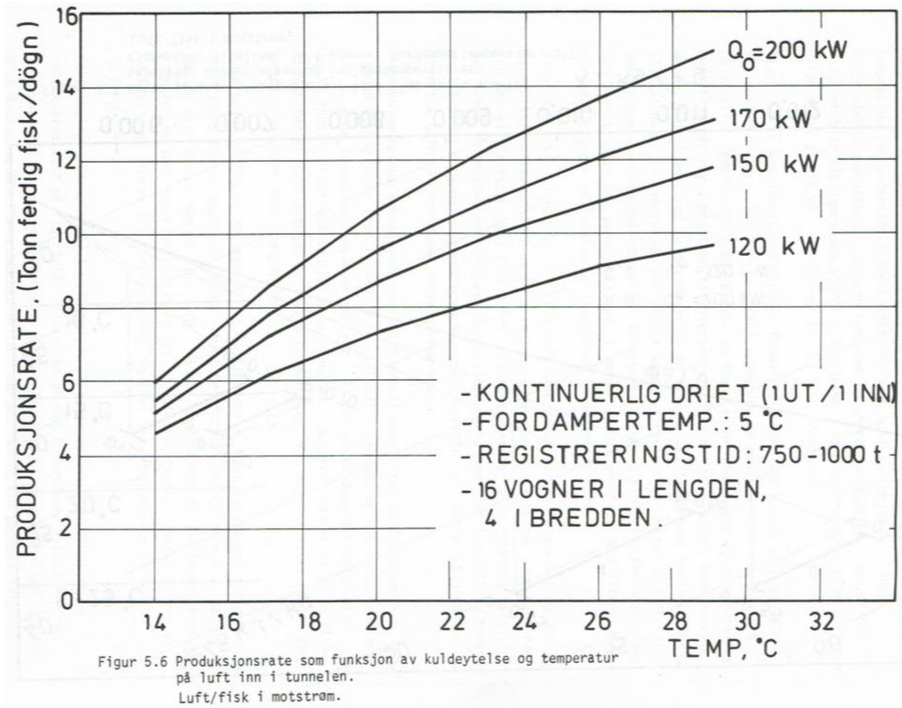

Figure 8.3 Production rate vs. temperature of dry air. (Cooling performance)

Again from his work, it can be obtained the Table 8.1, where it is shown that the power requirement is 39kW for a plant of 150 kW cooling performance. Electricity consumption per. tons of fish produced is 85.9 kW.

Q_o [kW]	W [kW]	p [tonn fisk / døgn]	E_1 [kWh / tonn fisk]	E_2 [kWh / kg H_2O fordampet]
200	52,1	13,7	91,3	0,49
170	44,2	12,1	87,7	0,47
150	39,0	10,9	85,9	0,46
120	31,3	9,1	82,5	0,45

Table 8.1 Cooling performance.

The following economic calculations are performed for both methods. As it has been already indicated, they are some rough calculations, as it is not taken into account certain additional costs of the process as indicated before. In addition, it must be kept in mind that the prices listed here may vary, depending on the provider of the facilities and devices. It should also be noted that the price of electricity is increasing in recent years.

With the cooling performance assumed of 150 kW, it has been obtained a power consumption of 85.9 kWh per ton of fish produced a day and a production of 10.9 tons of fish a day. It is assumed a production process of 250 operating days per year and energy costs of NOK 0.25 pr. kWh. Oil price is higher than electricity, nevertheless, as it has been stated before, the gap is narrowing down these last years. It is taken an oil price of NOK 0.414 pr. kWh for the calculations.

The results of the economic calculations are shown in Table 8.2, where the comparison is made. It can be observed that due to the great cost of the heat pump utility and the increase in electricity price, the total cost of the heat pump system is now larger than it would have been some years ago. However, since the total cost per year of the heat pump is NOK 96.976 and the total cost per year for the traditional system is NOK 114.918, the total difference cost between methods is NOK 17.939. The total cost per year comparison shows little advantage for the heat pump, but the savings that implies still favor the installation of the heat pump.

Costs (NOK)	Traditional boiler	Heat pump
Price with taxes	55.500	250.000
Delivery and installation	10.000	20.000
2 fans	8.760	8.760
Total capital cost	74.260	278.760
Energy cost of drying	96.908	58.519
Fan power costs	10.584	10.584
Total energy cost	107.492	69.103
10% amortization	7.426	27.876
Total cost per year	**114.918**	**96.979**

Table 8.2 Economic study comparison.

CHAPTER 9

CONCLUSION

9 CONCLUSIONS

The present Master's Thesis has been accomplished by studying the mechanisms involving the drying process of codfish. An energy study has been carry out to obtained a model to simulate the drying process that takes places in the drying chamber when drying food.

The drying process of the study is a combined air drying system with a heat pump supplemental drying system. The designed parameters for the simulation are a hot air temperature of 26 C, a relative humidity of air of 30% and air velocity of 2 m/s. the fish to be dried have a mass of 1 kg. The fish that enter the drying process are salted codfish, with an initial water content of 55%.

The simulation model allows changing the parameters of the chamber to be able to control the drying time, moisture content and other desire parameters of the drying process.

The most important conclusion that can be obtained after carrying out and evaluating all the simulations is that the optimal parameters for this drying process are, as it has been stated before, a temperature of 26 C, a relative humidity of 30% and air velocity of 2 m/s. This are the ideal parameters for a salted codfish of 1 kg, with an initial water content of 55%. The optimal temperature of the hot air is 26 C since the higher the temperature is, the better the heat exchange performance is obtained in the drying process. However, higher temperatures are not recommended due to quality requirements, since temperatures higher than 27 C spoil the fish by "burning" the surface. The optimal relative humidity of the air is 30% since it is of interest that the RH is as low as possible. Low relative humidity means higher heat transfer between the hot air and the fish. Therefore, the selected relative humidity is as low as it can get, but not lower than 30% to avoid a hard dehydrated zone. With these optimal parameters, the total drying time of the process is 18.67 hours.

Regarding the drying process, it is clear that the process is well divided in two phases with different mechanisms. In the first phase, when the water content is the highest, 55%, the surface of the fish is wet and there is only transfer from the moisture on the surface of the fish to the air in the chamber. When the moisture content decreases at the value of 50% the second phase takes part. There, dry zones on the surface of the fish start appearing, and apart from the surface-to-air transfer, there is also movement of the moisture in the inner layers of the fish, moving to the surface. The drying process reaches the end when the desired water content of 45% is achieved.

In this work, there have been done several simulations with the model to observe how the process changes when the parameters change, and therefore, to compare such results to be able to discuss and discern what the best options are.

There have been made simulations with different temperatures, keeping the rest of parameters unchanged, to observe the differences in the drying time. It has been noted that when the temperature decreases, the drying time increases, especially in the second phase. This behavior was expected, since, as it has been explained earlier, lower temperature means lower heat transfer. The results show that when the temperature is dropped to 21 C, the drying time increases to 21.75 hours; and when it is lowered to 16 C, the drying time increases as much as 26.25 hours.

There have also been made simulations with different relative humidity, with the rest of parameters maintained. Again, as it was expected, when the relative humidity increased to 40%, the drying rate decreased getting to higher drying time as 29.67 hours. Simulations have been made as well, with this high RH and the low temperatures, showing that with lower temperatures the drying rate does not decrease as much. However, the drying times are still much higher than with the optimal conditions.

Other simulations have been made regarding the velocity of the dry air. It has been noted that lower temperatures of air than 2 m/s slow down the drying process by not favoring the continuous exchange of heat and mass between surface of the fish and air.

Simulations have been made with a velocity of 1 m/s and the different temperatures, and the optimal result has been obtained for the optimal temperature of 26 C, achieving a high drying time of 33.00 hours. The opposite results have been obtained by increasing the velocity to 3 m/s, where the drying rate increases notably for the range of temperatures, being 26 C the optimal temperature, with a low drying time of 12.92 hours. The improvement in the drying time is remarkable. Nevertheless, other aspects must be taken into account. The economic improvement due to the increased of production can be in conflict with the operating costs and the increased fan capacity of the system.

The last simulations proposed aimed to calculate the possible changes in the process when the mass of the fish is changed. In this case, the mass has been increased twice its value, to 2 kg. All the parameters of the drying process have been maintained. It was observed that for both phases the behavior was, to a greater or lesser extent, maintained, with a final drying time about twice as large as the one for 1 kg fish, a drying time of 42.17 hours.

After comparing the results from the simulation model with several different cases from the experiments carried out by Strømmen in his work, the simulation is verifies and it can be concluded that the simulation model works properly for the different configurations.

The economic study shows that the heat pump installation for heating supplement implies savings for the process when compared to traditional heating systems, like the oil energy bases system used for the comparison.

CHAPTER 10

FUTURE WORK

10 FUTURE WORK

This work has been focused on the development and verifying of a simulation model for the combined hot air and heat pump drying system. That way, by changing the parameters on the model, results of the procedure can be obtained to verify the feasibility of the process according to the drying rates obtained.

A further development of this simulation model should be approached. In this simulation, the two phases comprising the drying process are calculated separately. A future work proposed should include both phases in the same simulation model so results would be obtained instantly.

This simulation model is supposed to ease the calculations, so by introducing the parameters of the process, one can determine the drying time of that process. Several combinations of changes of the parameters have been proposed, but further work should approach some other combinations of the parameters.

Some of the parameters susceptible to be changed that should be approached are the parameters related to the drying system used. Future simulations should consider different distributions of the chamber. This simulation has used a 1out/1in countercurrent process. Future work should give the possibility of selecting the kind of flow desired for the process (concurrent, countercurrent or crossflow), selecting whether the process is continuous or in batch, etc.

A more detailed with more specific data economic study should be conducted. This is because there have been compared the results of the various simulations conducted based on different combinations of parameters performed, but in some cases the economic aspects would have great influence in defining the optimum value of the observed parameter. Therefore, a detailed economic study of the specific combinations should be made, to discern and decide, taking into account the economical results of that proposed work and the energy results obtained in this Master's Thesis, what decision to make in the drying process to improve the results.

These future works proposed would be focused on the process of combined air drying with heat pump, but they could also approach other direction directly comparing different drying methods, taking into account the product specifications and environment, as well as other parameters already given.

As it has already been indicated in previous sections, there are many different types of drying systems and different combinations between them that may arise. This way, it can be compared the production, drying times and efficiency of various types of drying, to observe and determine the most effective drying method depending on the conditions raised.

In the case studied in this paper, it has been used a combined air drying with assisted heat pump drying system for salted cod. However, for drying other kind of fish or even cod as well which has not been previously salted (and would have higher initial water content), or under different conditions and configurations, it may be better the utilization of another drying method. Getting a simulation that compared different processes according to these conditions raised, immediate results would be obtained to facilitate decision-making.

CHAPTER 11
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11 BIBLIOGRAPHY

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