# Biomass Drying Cabinet
# -Design, Construction, and Evaluation-

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Faculty of Engineering and Natural Sciences
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2021

# Biomass Drying Cabinet
# -Design, Construction, and Evaluation-

Mohiodin Nazemi

60 ECTS thesis submitted in partial fulfillment of a
*Magister Scientiarum* degree in Mechanical Engineering

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# Abstract

For the purpose of pelletizing biomass and use it as a fuel in a gasifier, the moisture level of the material needs to be reduced to an acceptably low level (less than 20%). Therefore, biomass drying is necessary before pelletizing and gasification. In this project, we used a general engineering methodology to design a biomass dryer. This method included studying the gasification process, investigating various drying methods and strategies, designing a dryer, constructing a prototype, testing the prototype, and evaluating the design. AutoCAD and SOLIDWORKS were used in the design process. In this project, the gasification process was investigated, and the necessity of biomass drying was clarified. In addition, a biomass drying cabinet was designed, which can dry 50 kg of algae in 30 hours. A 9-kW electric heater with 980 cubic meters per hour airflow was used as a source of heat in the dryer. The preliminary design was equipped with a heat recovery system, which was removed after considering the results of the first test. The results of the drying test on the revised prototype were successful. The moisture content of algae reduced to 11.7% after 22 hours of drying. More than 50% of the mass of algae was lost in less than the first 6 hours of the drying test, and the drying rate reduced over time.

# Útdráttur

Til að köggla lífmassa og sem nota á sem eldsneyti í gasara þarf að rakastig lífmassans að vera passlegt (innan við 20%). Það er því nauðsynlegt að þurrka lífmassann áður en hann er kögglaður og gasaður. Í þessu verkefni beittum við verkfræðilegri hönnunaðferð við hönnun á þurrkara. Þetta fól í sér rannsókn á gösun, rýni í ólíkar þurrkunaraðferðir, hönnun þurrkara, smíði frumgerðar, prófanir á frumgerðinni, og mat á hönnuninni. AutoCAD og SOLIDWORKS voru notuð í hönnunarferlinu. Rýnt var í gösunarferlið í þessu verkefni og skýrð þörfin á þurrkun lífmassa. Að auki var hannað sérstakan lífmassaþurrkofn, sem getur þurrkað 50 kg af þörungum á 30 klst.. 9 kW rafmagnshitari sem hitað getur 980 rúmmetra af lofti á klst. var notaður til að hita þurrkofninn. Fyrsta útgáfan af þurrkofninum var með kerfi til að endurnýta hitann. Það kerfi var fjarlægt eftir að niðurstöður fyrstu prófunarofnsins voru ljósar. Niðurstöður prófunar á þurrkgetu endurskoðaðrar frumgerðar ofnsins sýna að hönnunin tókst vel upp. Rakainnihald þörunga minnkaði í 11,7% eftir 22 tíma þurrkun. Í fyrstu prófun þurrkferlisins hvarf meira en 50% af massa þörunganna á fyrstu 6 klst., en að þeim tíma loknum hægðist á ferlinum.

*This thesis is dedicated to my parents.*

# Preface

In the past few decades, global warming and climate changes have encouraged experts in the energy industry to investigate possible strategies to mitigate these problems. Since many people in my hometown were suffering from air pollution, which is a consequence of overusing fossil fuels, I was motivated to investigate the field of renewable energies in order to be a tiny part of a possible solution. In my opinion, biomass as a cheap source of energy, which is accessible everywhere, can be a feasible alternative for fossil fuels. This subject is an excellent introduction for me to begin research and study in this field.

Literature review, experiment, calculations, modeling, prototype construction, prototype test, design evaluation, and receiving advice from experts were the main processes in this project. This research is unique in drying field and contributes to this field of study since it answers some questions about the gasification process, reviews practical drying tactics, presents a dryer design, and discusses the results of drying tests. I hope this research helps researchers in this field.

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# Abbreviations

| Symbol | Parameter | Unit |
|---|---|---|
| C | Specific heat | J/kg.°C |
| F | Air flow | kg/s |
| K | Heat transfer coefficient | W/m.°C |
| $L_f$ | Latent heat | kJ/kg |
| L | Length | m |
| m | Mass | kg |
| $\dot{m}$ | Mass flow | kg/s |
| P | Power | W |
| Q | Energy | J |
| R | Humidity | - |
| r | Pipe radius | m |
| t | Time | s |
| T | Temperature | °C |
| V | Volume | $m^3$ |
| $\dot{W}$ | Rate of drying (water evaporation) | kg/s |
| X | Absolute humidity of air | gram (water)/kg (air) |
| $\rho$ | Density | $kg/m^3$ |
| MC | Moisture content | - |

# Acknowledgements

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I would like to thank my supervisor Rúnar Unnþórsson, for providing me the opportunity to work on a project that I deeply care about. He patiently answered all my questions and helped me to move forward on the right path during every stage of the project. I cannot imagine how I could have handled this work without his support.

I also would like to thank my supervisor Christiaan Petrus Richter, who has assisted me in any way he could. His office was always a good place for discussing and solving problems.

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Last but not least, my parents have always supported me, no matter how difficult my goals are, my gratitude to them can hardly be explained in words.

# 1 Introduction

Over the past few decades, the notion that switching from fossil fuels to more sustainable sources of energy is in fact necessary for future generations has become more prominent. Researchers are looking into biomass as a source of renewable energy and are seeking to convert it into more efficient fuel. Gasification can be applied as a practical solution for converting biomass energy into mechanical or chemical energy. The high moisture levels inherent in most types of biomass present significant challenges, namely, the high moisture levels reduce the efficiency of the gasification process (Amos, 1998). This work proposes a design for a biomass drying cabinet to reduce the amount of moisture within the biomass and prepare it for pelletizing and gasification. The design is tested and evaluated using a prototype.

With the rise of industrialization since the 19th century, experts in the field of sustainable energy have considered possible strategies to reduce the amount of greenhouse gas production by shifting to more sustainable energy options since the negative effects of greenhouse gases and climate changes are becoming more catastrophic in recent years (Zajec, 2009). Renewable energies are types of energies that usually are replenished by nature after usage and have fewer negative effects on the environment (Potsdam Institute for Climate Impact Research (PIK), 2012). Sustainable sources of energy guarantee the world long term power accessibility, decrease in budgets allocated to fossil fuels, as well as conserving fossil fuels for other usages and future generations. Renewable sources also eliminate the need to import and export fuel, decrease environmental disagreements, mitigate pollution, reduce greenhouse gas emissions, and provide more jobs for local populations (Turkenburg, o.fl., 2012).

Biomass is an organic substance with chemical energy content, which originates from living organisms such as plants. Time is a major difference between biomass and fossil fuels. While biomass might be available everywhere, fossil fuels can be found deep down in the earth. For example, sawdust, straw, manure, textile scrap, sewage sludge, food waste, wastepaper, etc. are all different types of biomasses. The life cycle of biomasses generally shows a balance between carbon emission and carbon absorption. Therefore, it is considered a renewable source of energy as long as consumption and production are well managed (Hadera, 2011). Sustainability and adaptability are, among numerous different aspects, significant points of interest concerning a fuel source. In addition, biomass resources have more accessibility around the globe in comparison with other renewable sources. Hence, biomass can be utilized as a source of heat and power as well as being converted to biofuels through various processes such as gasification (Ladanai & Vinterbäck, 2009).

At the present, researchers seek to produce energy from biomass by applying the knowledge of thermal incinerators. Gasification and pyrolysis are among the most efficient processes in this field (Zajec, 2009). The process of gasification changes carbonaceous materials into syngas by applying heat and pressure. This process includes an endothermic reaction in a reducing (oxygen-deficient) condition. Syngas consists of CO, H2, CH4, tars, inorganic impurities, and particulates. It can be used in internal combustion engines and gas turbines.

Hence, the conversion of material with untapped potential to a well-prepared fuel (syngas) is a major goal of the gasification process (Basu, 2010). Nonetheless, some processes such as drying need to be performed on biomass to prepare them for usage before gasification.

Separating moisture from the biomass plays an important role throughout the whole procedure. The use of dry biomass in gasification renders the whole process more efficient, reduces the required energy to achieve a gaseous state, improves syngas thermal quality, and produces less pollution. (Amos, 1998). However, these procedures are not without challenges. For example, tar formation in the syngas can occur in the biomass gasification process. High moisture levels in the biomass often compounds the problem. In addition, the higher moisture levels present within the biomass necessitates more heat for evaporation and consequently, less syngas will be produced (Kirsanovsa, Žandeckisb, Blumberga, & Veidenbergs, 2014). Therefore, a drying process in order to properly prepare the biomass seems necessary prior to gasification. In this project, a biomass drying cabinet is designed based on research of drying techniques for the purpose of reducing the moisture level in biomass. Thus, biomass humidity is an effective parameter in the gasification process that needs to be carefully controlled.

Experts in the field of gasification believe that drying biomass improves the gasifier´s performance. Using biomass for gasification as well as producing syngas from these materials such as waste wood is a perfect example of waste valorization, which is one of the goals of this project. As more and more countries show interest in using biomass as fuel, the more the need for effective uses of biomass grows. This bodes well for the future of sustainable energy. In this study, various drying techniques will be studied and compared, and the most suitable of them will be applied for the creation of a biomass drying cabinet.

## 1.1 The research questions

The primary research question this project will seek to answer is: In what ways can the inherent levels of moisture within a biomass be reduced to the optimal levels for both pelletizing and gasification. In order to answer this question satisfactorily, several factors must be established. First, a definition of what the gasification process is, and why it is necessary to dry biomass before gasification must be put forth. Second, this paper will consider and evaluate various methods and mechanisms of drying. Properly defining terms and considering which process of drying biomass is most suitable, will allow us to consider which design is most appropriate for the dryer. It is necessary for each design to be tested and evaluated. Consequently, we need to conclude what is the best approach to construct a prototype of the design to test and check its performance. Therefore, the primary question, is how we intend to lower the moisture level in the biomass to prepare it for the gasification process.

## 1.2 The research goals

At the end of this project, we expect to create a simple design of the drier, which has been tested and approved based on the results of the test. The goal is to design a drier, which can reduce the moisture content of biomass to less than 20% by using heated atmospheric air within an economically feasible time. In order to attain these results, an introduction about the gasification process and various drying mechanisms is indispensable. In this study, we investigate similar works and study their procedure to find the method, which is most suitable for our project.

In addition, the potential indirect impacts of this research are far-reaching. For example, converting biomass into energy is a kind of waste valorization, which is an indirect goal for this project. Biomasses are materials such as sawdust, waste wood, wastepaper, animal manure, etc., which are usually considered useless. Therefore, producing energy from waste substances can be a valuable indirect goal for this project. Furthermore, replacing fossil fuels by biomass and reducing greenhouse gas emissions are other potential goals for this research.

## 1.3 The research overviews

In this report, various topics related to biomass drying are considered. In the second chapter, the gasification process as a method for extracting energy from biomass is introduced. Third chapter basically describes biomass drying. The main methods and mechanisms for drying biomass are discussed in this chapter. In chapter four, the applied methods in this study are explained, and the assumptions, boundaries, and constraints of the study are discussed. Furthermore, the required formulas, materials, and software are described. Chapter five is dedicated to experiments, calculations, and modeling. Several models for the dryer are presented and a preliminary design is released at the end. Chapter six introduces a prototype of the preliminary design. The prototype is tested, and the results of the test are analyzed in this chapter. Chapter seven is dedicated to the main drying tests. The revised prototype is tested and evaluated. In chapter eight, the final design of the biomass drying cabinet is presented according to the results of the tests in the previous chapter. In the concluding chapter, the main conclusions are illustrated and discussed. The last chapter recommends some relevant topics for future studies.

# 2 Thermochemical methods for extracting energy from biomass

To produce energy from biomass, biochemical or thermochemical processes are needed. As a result of applying high temperature and pressure in thermochemical processes such as gasification, well-prepared fuel can be produced from biomass (Safarian, Richter, & Unnthorsson, Waste Biomass Gasification Simulation Using Aspen Plus: Performance Evaluation of Wood Chips, Sawdust and Mixed Paper Wastes, 2019). Combustion, pyrolysis, and Liquefaction are other methods for converting biomass into useful forms of energy. These are similar processes that differ in required oxygen and temperature of the reaction (Hadera, 2011).

Combustion is an exothermic reaction between oxygen and hydrocarbon when biomass is input material and the output product is $H_2O$ and $CO_2$. The most common method for electricity generation is to produce superheated steam in a boiler by burning biomass and applying a turbine to change thermodynamic energy to mechanical energy and rotate the rotor in a generator (Basu, 2010).

The thermal decomposition of biomass into three different phases in absence of oxygen is called pyrolysis. Slow pyrolysis, Mild pyrolysis (Torrefaction), and Fast pyrolysis are three types of this process. In pyrolysis, the larger molecular structure of hydrocarbons breaks into smaller ones. In Fast pyrolysis liquid fuel (bio-oil) is the main product, while in Slow pyrolysis gas and solid charcoal are produced. Pyrolysis is an economical method for transforming waste biomass into more valuable fuels (Basu, 2010).

Liquefaction is a process for converting solid biomass into liquid fuel, which can be done through pyrolysis, gasification, and hydrothermal process. The hydrothermal process can be done by keeping a mixture of biomass and water at high temperatures (300-350 °C) and high pressure (12-20 MPa) for a period (Basu, 2010).

In this chapter, we will focus on the gasification process to clarify the reasons behind biomass drying. The gasification mechanism, various types of gasification, and gasification agents will be explained. In addition, the benefits of this process over other similar processes will be discussed in the following sections.

## 2.1 Gasification

Gasification is a procedure for producing syngas. Syngas production is a multistage chemical operation in that biomass is passed through pyrolysis, oxidation, and hydrogenation processes (Kirsanovsa, Žandeckisb, Blumberga, & Veidenbergs, 2014). In gasification process biomasses convert into more advantageous fuels and substances by applying heat and pressure (Safarian, Richter, & Unnthorsson, Waste Biomass Gasification Simulation Using Aspen Plus: Performance Evaluation of Wood Chips, Sawdust and Mixed Paper Wastes, 2019). This process needs an intermediate gas such as supercritical water to rearrange the molecular structure of the feedstock. The intermediate gas can consist of air, oxygen, water, or a mixture of these items. The gasification process includes exothermic reaction (combustion reactions) that converts chemical energy in the feedstock to heat energy. Subsequently, a fraction of this heat energy is converted back into chemical energy in the syngas (mostly CO, H2 and a small number of hydrocarbons like CH4) by endothermic reactions in the hot and oxygen lean reduction zone (Basu, 2010).

If we consider the nature of the processes, we can name three methods for converting biomass into a prepared fuel. These methods consist of thermochemical, biochemical, and mechanical extraction methods. Combustion, gasification, pyrolysis, and liquefaction are in the thermochemical group. Figure 2.1 shows various methods (Safarian, Unnthorsson, & Richter, Hydrogen production via biomass gasification: simulation and performance analysis under different gasifying agents, 2021). Gasification processes are different according to gasifier type and gasifier agent. Fluidized beds, entrained flow beds, and fixed bed gasifiers are the most common types (Kirsanovsa, Žandeckisb, Blumberga, & Veidenbergs, 2014).

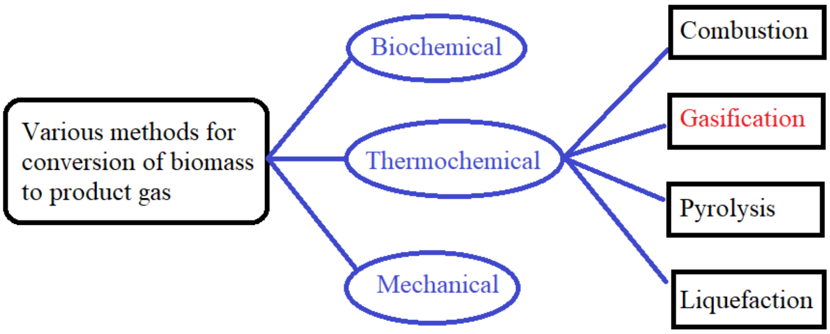


*Figure 2.1- Various methods of biomass conversion into product gas (Safarian, Unnthorsson, & Richter, Hydrogen production via biomass gasification: simulation and performance analysis under different gasifying agents, 2021)*

Drying, pyrolysis, char gasification, and combustion are four steps in the gasification process. These steps do not happen separately, and often overlap each other. In a downdraft gasifier, as an example, steam and oxygen or air flow into the lower part of the gasifier, while biomass is fed from the top. The products of pyrolysis and combustion (high temperature gases) flow downward over the remaining char and gasification happens at the lower section. Figure, 2.2 illustrates a schematic mechanism of the gasification process in a downdraft gasifier (Basu, 2010).

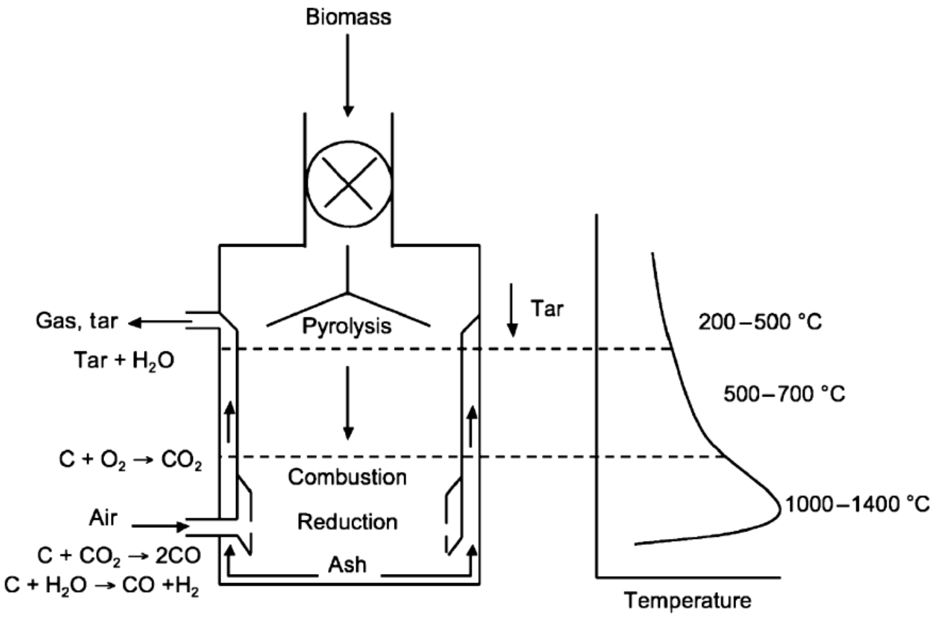


*Figure 2.2- Gasification reaction in a downdraft gasifier (Basu, 2010)*

During gasification, an uncompleted oxidation at high temperature (600°C – 1700°C) performs that transforms plant-based components to a synthesis gas (syngas), which consist of CO, $H_2$, $CH_4$, tars, inorganic impurities, and particulates. Syngas can be used in internal combustion engines and gas turbines (Safarian, Unnthorsson, & Richter, Techno-Economic Analysis of Power Production by Using Waste Biomass Gasification, 2020).

In other words, as the hydrogen content of a fuel increases, it lowers the vaporization temperature and raises the likelihood of it being in a gaseous state. In gasification process the ratio of carbon to hydrogen in the molecular structure of the fuel decreases through both direct and indirect method. In the direct method, the fuel is exposed to hydrogen at high pressure, while in the indirect method, it is exposed to water vapor at high pressure and high temperature (Basu, 2010). Different types of gasifiers can be designed based on direct or indirect method.

### 2.1.1 Gasification feedstock

Various types of biomass can be used to feed the gasifier machine. Charcoal, wood chips, briquettes, pellets, etc. are more common raw materials for the gasification process. Briquette is a compressed block of coal dust or other combustible biomass material (e.g. charcoal, sawdust, wood chips, peat, or paper). In this section we focus on pellets as a more common feedstock for the gasification process.

Pellet fuels (or pellets) are biofuels made from compressed organic matter or biomass. Pellets can be made from any one of five general categories of biomass: industrial waste and co-products, food waste, agricultural residues, energy crops, and virgin lumber. Pellets are categorized by their heating value, moisture, ash content, and dimensions. They can be used as fuels for power generation, commercial or residential heating, and cooking. Pellets are extremely dense and can be produced with a low moisture content (below 10%) that allows them to be burned with a high efficiency (Manomet Center for Conservation Sciences, 2010).

Pellets are produced by compressing the biomass which has first passed through a hammer mill to provide a uniform dough-like mass. This mass is fed to a press, where it is squeezed through a die having holes of the size required (normally 6 mm diameter, sometimes 8 mm or larger). The high pressure of the press causes the temperature of the wood to increase greatly, and the lignin plasticizes slightly, forming a natural "glue" that holds the pellet together as it cools (Manomet Center for Conservation Sciences, 2010). Many parameters need to be considered in order to produce a high-quality pellet for the purpose of gasification.

### 2.1.2 Gasification agents

As mentioned before, the gasification process needs an agent to be processed. Gasification intermediate fluid or gasification agent provides oxygen for the process. They react with solid carbons as well as heavier hydrocarbons and break them to low-molecular-weight gases (Basu, 2010). Air, steam-oxygen, or air-steam can be applied as gasification agents. The produced syngas has a higher heating value in the case of using steam as an agent for gasification. However, the cost of syngas production is higher in this case. The ratio of steam to biomass is an influential factor in the gasification process when steam is the agent. The increase in steam to biomass ratio increases the specific weight of $H_2$, CO, carbon conversion, syngas calorific value, and gasification efficiency. However, the tar content of syngas also rises. Therefore, it is important to consider all aspects, while selecting the gasification agent (Kirsanovsa, Žandeckisb, Blumberga, & Veidenbergs, 2014).

### 2.1.3 Tar formation in syngas

Tar formation in syngas, due to three main reasons, is highly undesirable in the gasification process. First, tar condensation inside the ducts can damage the equipment. Second, it emits fine solid particles in the air. Third, tar polymerizes into more undesirable structures (Basu, 2010). Many researchers are investigating the possible methods to remove tar from syngas. The amount of produced tar in gasification depends on the design of the gasifier, process condition, and biomass properties (Kirsanovsa, Žandeckisb, Blumberga, & Veidenbergs, 2014).

James et al. studied the performance of an updraft gasifier (In an updraft gasifier, the gasification agent flows in from the bottom and depart from the top). They used pine woodchips as biomass to feed the machine. Biomass particle size, biomass moisture level, and biomass density were input parameters for analyzing the amount of biochar production, biomass consumption rate, syngas composition, and the amount of tar production. It was certified that using a larger particle size for biomass will lead to an increase in the production of biochar and at the same time larger particle size will increase the tar content, which is not a positive result. Despite the increase in the amount of tar, produced hydrogen was at its minimum level when using a larger particle size of biomass. They concluded that using biomass with an optimum level of moisture will decrease both biochar and tar at discharge. Likewise, the composition of carbon monoxide in syngas reduced by controlling the moisture at an optimum level. They added that the amount of $H_2$ and CO in the syngas produced by top-lit updraft gasifier was not as much as $H_2$ and CO generated from conventional gasifiers (James R., Yuan, & Boyette, 2016).

James et al. used a 10.1 cm internal diameter steel gasifier column with 152 cm height. A 1.5 kW air compressor equipped with 18.9 L reservoir was used to supply operational pressure. The airflow of 20 lpm at atmospheric pressure was applied for the operation. Figure 2.3 illustrates the gasifier and different parts (James R., Yuan, & Boyette, 2016).

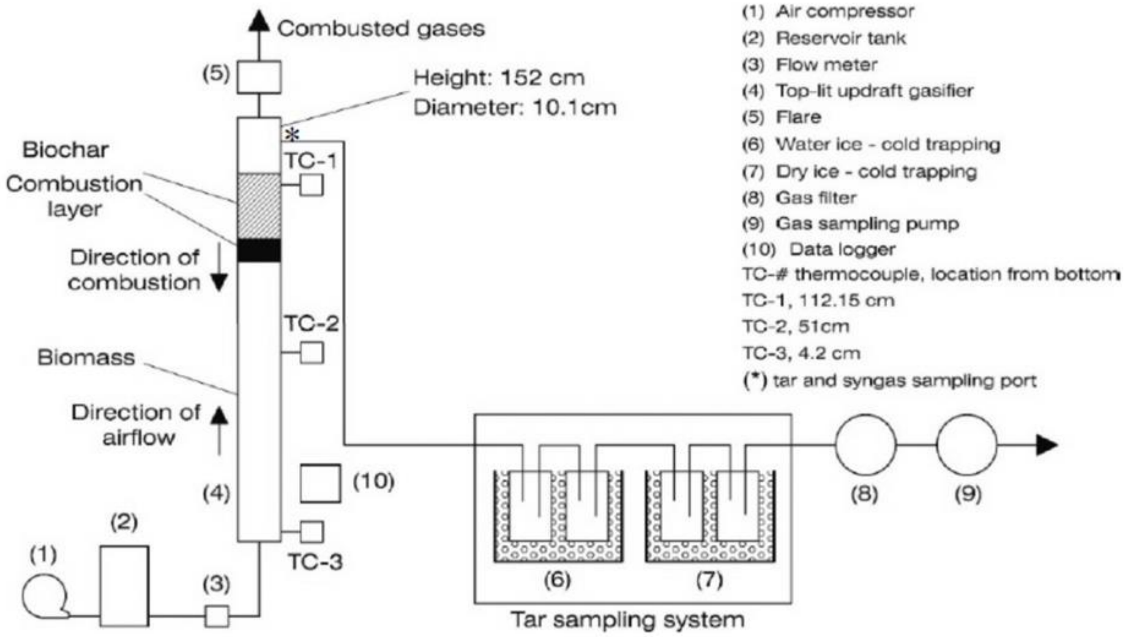


*Figure 2.3- Schematic figure of updraft gasifier (James R., Yuan, & Boyette, 2016)*

The composition of produced syngas in the gasification process is not always identical. Generally, there are various parameters that affect the gasification process and syngas composition. As mentioned above, the design of the gasifier, the condition of the process, and biomass features are influential parameters in the gasification process. Furthermore, the gasifier size can be optimized to attain perfect fuel conversion. The biomass feeding mechanism is also determinative in the composition of produced syngas (Kirsanovsa, Žandeckisb, Blumberga, & Veidenbergs, 2014).

### 2.1.4 Gasification efficiency

The ratio of produced gas over the amount of consumed biomass, express the efficiency of the gasification process (Basu, 2010). The efficiency of gasification depends on many parameters. The equivalence ratio (ER), the reactor temperature, and biomass moisture level are the most important factors. ER is the ratio of the actual air/fuel ratio to the stoichiometric air/fuel ratio. These parameters affect each other. Any changes in these parameters affect other parameters and syngas composition. Hence, an optimum point for all factors can result in maximum efficiency for the process (Kirsanovsa, Žandeckisb, Blumberga, & Veidenbergs, 2014).

### 2.1.5 Gasification main benefits

The gasification process is more efficient for electricity generation than conventional methods such as incineration. The gasification process emits fewer pollutants and produces syngas, which can be used in internal combustion engines and gas turbines. Therefore, waste biomass gasification can be a promising method for energy production in remote areas, which need electricity and heat (Safarian, Unnthorsson, & Richter, Techno-Economic Analysis of Power Production by Using Waste Biomass Gasification, 2020).

In addition, the gasification process is a clean and productive technology for hydrogen production. This is a relatively fast process, which is efficient likewise (Safarian, Unnthorsson, & Richter, Hydrogen production via biomass gasification: simulation and performance analysis under different gasifying agents, 2021).

The gasification process can have some other applications, which are mentioned below:

- To separate noncombustible gases like nitrogen and steam from the material and enrich the fuel.
- To separate pollutant gases such as sulfur and nitrogen from the fuel to prevent contaminating the atmosphere while burning.
- To increase hydrogen to carbon ratio in the molecular structure of the fuel (Basu, 2010).

According to some research, low-capacity biomass gasifiers coupled with electricity generators can be possible both technologically and economically in off-grid areas in Iceland (Safarian, Unnthorsson, & Richter, Techno-Economic Analysis of Power Production by Using Waste Biomass Gasification, 2020).

## 2.2 Chapter summary

The gasification process is a process for converting organic waste materials to more accessible forms of fuels in a way that emits less pollution in comparison with other similar processes. In this chapter, the gasification process was discussed, and other thermochemical methods were briefly introduced. The gasification process, gasification agents, tar formation, gasification efficiency, and advantages of this process were explained in this chapter. In addition, some related works were reviewed, and their results were briefly mentioned. As we learned from this chapter, biomass preprocessing is very important for efficient gasification. In the next chapter, we will study the pros and cons of different biomass drying techniques.

# 3 Biomass drying

Biomass gasification is a precise process that is done by a gasifier machine. All gasifiers share specific standards concerning which material is suitable for input. These standards include moisture level in biomass, particle size of material, and biomass density. For the purpose of preparing biomass for gasification, several processes should be performed to ensure continuous and steady gasification. Otherwise, the gasifier might be damaged and halt the process or the process is not efficient enough. Drying is an important process for preparing biomass before the gasification, which improves both the process's performance and the quality of produced syngas. In this chapter, first we will briefly discuss the necessity of drying and then will review the drying methods, drying media, and drying techniques.

## 3.1 The necessity of drying

Experts, who are working on gasification process, agree that biomass needs to be preprocessed before consumption as a fuel. Drying is a primary process before gasification. Using sunlight for drying wood or rice straws was a common method in the past. Lately, new plant-based materials such as fruit waste, sludge, or microalgae with a high level of moisture are being dried to be used as biomass. It has been reported that high level of moisture in biomass not only reduce the efficiency of the process, but also can disrupt the whole process (Gebreegziabher, Oyedun, & Wai Hui, 2013).

When gasifying wet biomass, the process temperature decreases, and the gasification process cannot be done completely (Gebreegziabher, Oyedun, & Wai Hui, 2013). Wood-based biofuels in comparison with compressed biomass release more particulates while gasifying due to higher moisture level (Ståhl , Granström , Berghel , & Renström, 2004). Another disadvantage of gasifying wet biomass is that the produced syngas has lower quality since wet biofuel deteriorates the performance of the process (Brammer & Bridgwater, 2002). At higher temperatures more tar in contact with oxygen is converted to non-condensable gases. Therefore, wet biomass decreases the tar conversion into non-condensable gases in the process since the high level of moisture cause temperature reduction in reactor (Basu, 2010).

Gebreegziabher et al. worked on finding the optimum point of biomass drying using a mathematical model. Their model is based on material and energy balances, heat transfer, and kinetics. Figure 3.1 illustrates the flow diagram of the process. They designed a drying process to dry 5000 kg/h of poplar sawdust from 50% to 20%. The lower heating value (LHV) of humid sawdust can be calculated by finding the difference between the enthalpy of water vapor in the flue gas and the LHV of dry sawdust (Gebreegziabher, Oyedun, & Wai Hui, 2013).

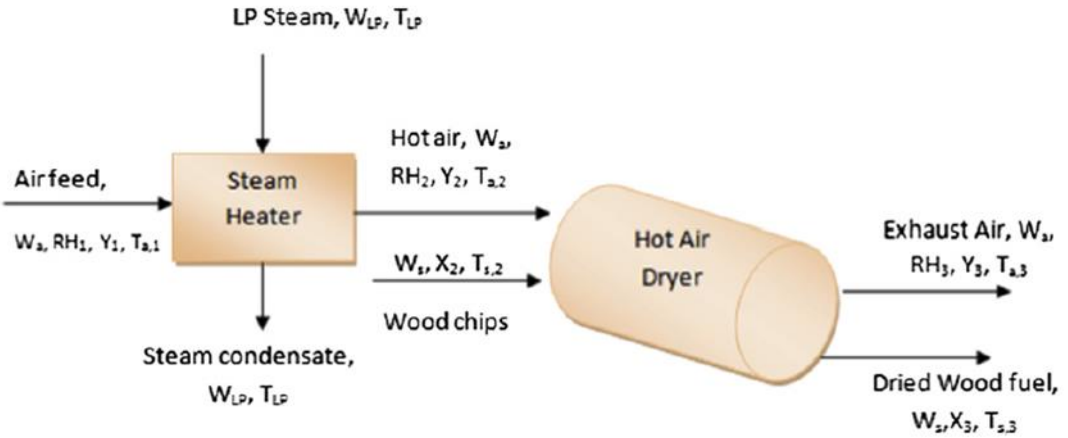


*Figure 3.1-Biomass drying flow diagram (Gebreegziabher, Oyedun, & Wai Hui, 2013)*

## 3.2 Drying medium

The drying process can be time-consuming when using heated air but can take only a few minutes by blowing high temperature gas through the material (Gebreegziabher, Oyedun, & Wai Hui, 2013). Drying medium or drying intermediate fluid is a fluid, which performs the heat transfer and mass transfer in the drying process. Dryers can be classified into different categories based on which fluid is used in the drying process. Using water vapor as a medium is more efficient than using air or gas because it poses no danger of fire or explosion. In addition, steam condensation poses a unique advantage in comparison with air and gas because it alleviates separation of toxic or useful liquid. However, using water vapor in a dryer needs more complicated systems with higher maintenance requirements. Briefly, drying intermediate fluid is a determinative factor in drying process (Ståhl , Granström , Berghel , & Renström, 2004).

## 3.3 Drying methods

There are various methods for separating or removing moisture from materials. Some of methods are mostly used for drying foods such as fruits or nuts that might not be economical to be used for biomass drying. Convective drying, microwave vacuum drying, freeze drying, osmotic dehydration, spray drying, infrared radiation drying, explosion puffing drying, etc. are the most common methods of drying (Si, o.fl., 2015). Convective drying, which consist of heat and mass transfer, by circulating a drying medium through the material is a common method for biomass drying. In this study we focus on convective drying.

Selecting the source of heat, the strategy for separating the evaporated water, and the method of exposing wet materials to the heated medium are three basic parameters while designing a dryer. Generally, the drying process can be classified into two categories according to the method they use to supply heat for drying.

### 3.3.1 Direct drying

In direct dryers, the wet material is in direct contact with the heated medium (either hot air or superheated water). Direct dryers have two main types: air and superheated steam dryers. The air is in direct contact with wet material in air dryers. The air temperature reduces and provides latent heat for the moisture inside the material to evaporate. The separated moisture leaves the dryer with air. The wet material can have more contact with the air by mechanical tactics such as rotary drums (Amos, 1998).

### 3.3.2 Indirect drying

In indirect drying there is only heat transfer between wet material and hot fluid and no direct contact. An advantage of indirect drying is that recycling the heat is easier in comparison with direct drying since the steam is not mixed by the intermediated fluid. This process can be done by vacuuming the steam from the dryer chamber and capturing the latent heat (Amos, 1998).

## 3.4 Techniques for drying biomass

For the purpose of choosing the appropriate dryer, several factors can be considered. Particle size and specifications of the biomass, budget, operation and maintenance, efficiency, environmental concerns, available space, etc. are some of the main factors when choosing the dryer. Different drying fluids such as superheated steam, hot air, or hot water can be applied in any kind of dryer. In this section, some of the main types of dryers are briefly introduced (Roos, 2013).

### 3.4.1 Tray dryers

Tray dryers are mostly utilized for drying a batch of solid materials such as food. They often include several trays (depending on the machine's size), which are located inside an insulated compartment. Hot air enters by a fan or natural flow, and high humid air with a lower temperature leaves the compartment in a tray dryer. Heat recovery is possible by recirculating a percentage of the outlet air and sending it back to the chamber. Some types of dryers have fixed trays that cannot be moved, and others have moveable trays. Tray dryers are affordable and simple (Misha, Mat, Ruslan, Sopian, & Salleh, 2013).

Dhanushkodi et al. focused on the design and construction of a cashew kernel dryer. They used a biomass burner for heating the drying air. They evaluated the machine by drying 40 kg of cashew kernels. An indirect heating method was used in this dryer. They controlled the temperature by biomass feed and used a variable-speed blower to control the airflow. Figure 3.2 shows the dryer cabinet and other components. Their experiments showed that the moisture reduction of cashews from 9% to 4% was achieved within 7 hours. Their dryer could maintain the temperature between 70 to 75 °C. The efficiency of the dryer was 9.5 percent. This number is the efficiency of the system that can be defined as the ratio of the required energy for the moisture evaporation to the total heat consumed in the drier. In conclusion, they added that it is possible to improve the efficiency by utilizing both solar heat and the biomass burner simultaneously (Dhanushkodi, Wilson, & Sudhakar, 2015).

*Figure 3.2- Cashew kernel dryer with biomass heater (Dhanushkodi, Wilson, & Sudhakar, 2015)*

### 3.4.2 Rotary drum dryers

In this type of dryer, materials receive heat while being agitated in a long rotating drum. The rotation of the drum is slow enough to let material fall down at the highest point inside the drum and maximize the material exposure to drying medium. Rotary drum dryers are the most common types of dryers. They are suitable for drying in huge capacities, although material moisture is difficult to control in this type of dryer. Various particle sizes of biomass can be fed into this dryer. Rotary dryers have a rather large footprint (Roos, 2013).

#### Direct-fired rotary dryers

In this technique, the highest possible temperature (around 260-430 °C) is applied in order to attain maximum efficiency. This temperature should not burn the material. Outlet air temperature in this type of dryer can reach up to 65 °C. Direct-fired rotary dryers need lower operation and maintenance however, they emit more pollution, have more fire risk, their exhaust air needs to be filtered, and reusing the waste heat is more complicated in these types of dryers (Roos, 2013).

#### Indirect-fired rotary dryers

This type is similar to the previous one. The only difference is that tubes inside the drum transfer heat indirectly from steam to the material. In other words, the hot medium does not mix with the material. Generally, this method is less efficient than the direct type, it requires more operation and maintenance, and produces less pollution (Roos, 2013).

Havlík and Dlouhý focused on indirect biomass drying. They compared drum dryers and rotary dryers. In the drum dryer, rotation of a paddle inside the drum agitates the material to speed up the drying process, while in a rotary dryer, material agitate by the rotation of the whole dryer. Havlík and Dlouhý designed and constructed a laboratory-scale drum dryer with indirect electric heating to certify their experimental results. According to this design, an early model of a pilot steam-heated rotary dryer was designed and built. Figure 3.3 shows the steam-heated rotary dryer (Havlík & Dlouhý, 2020).

*Figure 3.3- Steam-heater rotary dryer (Havlík & Dlouhý, 2020)*

They certified that the drying capacity increases with an increase in dryer filling ratio. They also admitted that using square evaporation capacity for designing indirect dryers is more desirable since the volume of evaporation capacity defines the mechanism of direct dryers more accurately. Square evaporation capacity defines as below:

Square Evaporation Capacity = EC = $m_{ev}$ / A.t

Where $m_{ev}$ is evaporated water, t is drying time, and A is heated area (Havlík & Dlouhý, 2020).

They concluded that the square evaporation capacity reduces when the diameter of the dryer increases. According to their results, it is more efficient to have an indirect dryer with a slimmer and longer (smaller diameter) shape (Havlík & Dlouhý, 2020).

### 3.4.3 Conveyor dryer

In this type of dryer, a perforated conveyor carries the biomass inside the dryer, while the drying medium is blown through the material by fans. Conveyor dryers have the capability to dry various types of materials. The emission of volatile organic compounds (VOCs) in conveyor dryers is lower than other types since they do not agitate material while drying (Roos, 2013).

Since the operation of conveyor dryers is possible at lower temperatures, they can use waste heat better than rotary dryers. In vacuum conveyor dryers, the inlet temperature can be as low as 12 °C higher than the surrounding temperature. Due to their low-temperature operation, they can use waste heat from a boiler stack economizer in order to minimize the waste of energy (Roos, 2013).

In multi-pass conveyor dryers, several conveyors in a cascade arrangement make a drying cycle for material to occupy less space. These types of dryers, due to their lower capital cost, have a smaller footprint in comparison with rotary dryers, which are frequently used in industries (Roos, 2013).

### 3.4.4 Cascade dryers

In cascade dryers, which are often used for drying grains, the material is exposed to an upward flow of hot air inside a drying chamber. The flow of hot air blows the material up in the chamber. There are openings on the side of the chamber for moving out the material. Cascade dryers work at higher temperatures than conveyor dryers and lower temperatures than rotary types. On the one hand, cascade dryers have smaller footprint than rotary and conveyor dryers. On the other hand, they have a higher risk of corrosion and erosion and consequently need more maintenance. Recycling heat in these types of dryers is likewise not easy (Roos, 2013).

### 3.4.5 Flash dryers

In flash dryers, hot air with high velocity dries the material in a short period. Cyclones are often used to separate materials floating in the air using centrifugal force. Due to the fast process in flash dryers, the equipment is less spacious in comparison with rotary dryers. However, they consume more electricity to produce high-velocity air. In addition, the particles should not have large sizes in order to stay floating in the air stream (Amos, 1998). Flash dryers have uniform product quality and smallest footprint. However, the installation budget is relatively high and reusing heat is not easy (Worley, 2011).

### 3.4.6 Superheated steam dryer

The only difference between superheated steam dryers and flash dryers is that the drying fluid in the superheated steam dryer is steam but in the flash dryer is flue gas. The steam does not condense since the temperature is always higher than the saturation temperature. Therefore, the outlet steam has a larger quantity and lower temperature than inlet steam. Heat recovery is possible by discharging the excess amount of outlet steam and reheating the rest. Sometimes this excess steam also can be used for another purpose such as washing or heating. Material feeding in the superheated steam dryer is possible by a pressure-tight feeder, like a screw feeder. This type of dryer does not emit any type of pollution, does not have fire risk, and has a small footprint (Roos, 2013). In addition, controlling the moisture level of material in a superheated steam dryer is easier. In this type of dryer, despite easy operation, there is a high potential of facing problems concerning leakage (Worley, 2011).

## 3.5 Comparing various type of dryers

Table 3.1 compares various types of dryers. According to this comparison, flash dryers and superheated steam dryers have the smallest footprint, rotary drum dryers have the highest range of temperature, tray dryers have the simplest mechanism, and conveyor dryers have the highest installation and maintenance cost.

*Table 3.1- Comparing various dryers (Worley, 2011) (Roos, 2013) (Misha, Mat, Ruslan, Sopian, & Salleh, 2013)*

| | **Drying medium** | **Working temperature** | **Installation and maintenance cost** | **Fire risk** | **Electricity consumption** | **Drying material** | **General footprint of product** |
|---|---|---|---|---|---|---|---|
| **Tray dryer** | Air | 40-80 °C | Low | Low | Low | Biomass<br>Vegetable<br>Fruits, nuts | Small footprint |
| **Rotary drum dryer**<br>**Direct fire** | Air heated by Waste gas or direct flame | 260-430 °C | Moderate | High | Low | Various types of Material | Large footprint |
| **Rotary drum dryer**<br>**Indirect fire** | Superheated<br>Steam | Less than<br>Direct fire rotary dryers | High | No risk | Low | not sticky materials | Large footprint |
| **Conveyor dryer** | Air,<br>Superheated steam | 40-120 °C | Highest | Low | High | Various types of material | Large footprint smaller than rotary |
| **Cascade dryer** | Air | Between rotary dryers<br>& Conveyor dryers | High | Low | Low | Mostly Grains-<br>Uniform particle sizes | Smaller footprint than rotary and conveyor dryers |
| **Flash dryer** | Air | Depend on design | High | Low | Very High | Not large particle size | Smallest footprint |
| **Superheated steam dryer** | Superheated steam | Depend on design | High | No risk | Very high | Not large particle size | Smallest footprint |

## 3.6 Chapter summary

Drying as a major preprocess was addressed, and several drying techniques were explained in this chapter. Some of the related studies were reviewed in this chapter as well. Among all technologies, we can conclude that rotary drum dryers are the best choice for a large quantity of biomass, cascade dryers are ideal for grains, flash dryers are efficient for producing products with consistent quality, superheated steam dryers have considerable potential for heat recovery, and tray dryers are inexpensive and easy to construct. All in all, we decided to use the tray dryer technique for this project due to its straightforward procedure. In the next chapter, we will explain the research method and will discuss the assumptions, boundaries, and constraints of this project.

# 4 Methods and Materials

The methodology used here is the standard engineering problem solving methodology: Identifying the problem, formulating the problem, solving the problem, and evaluating the solution. This is a cycle, which must be repeated to improve the solution. In this study, high level of moisture in biomass is the problem; calculations and research can formulate the problem; brainstorming a design for the biomass dryer based on calculation and research provide the solution. Evaluating the solution by experiment and analyzing the results determines how effective the solution is. If results are acceptable then the project is completed otherwise the cycle will be repeated in order to improve the solution. In this chapter, we will explain the method and introduce the required equipment of the project. In addition, we discuss the assumptions, boundaries, and constraints. We will review applied formulas, materials, and software as well.

## 4.1 Problem solving approach in engineering

Four stages of solving engineering problems are explained below.

### 4.1.1 Identifying the problem

Before beginning to think about the problem and considering possible solutions, the main problem between all consequences must be identified. After identifying the major problem, engineers might not be distracted by other problems and focus on the main one to solve it (Staniewicz, 2013). In this study, the high moisture content in biomass is the problem. Inefficient performance of gasification process, as an example, is the consequence of high moisture level in biomass and should not be considered as the main problem.

### 4.1.2 Formulating the problem

Formulating consists of several procedures: defining the borders of the problem and expressing those ranges by functions, reviewing, and checking the assumptions in the problem, defining the goals of the work, and finding the constraints of the problem. In this project, the amount of biomass and the percentage of reduction in humidity are the frameworks of the project. The major aim of the project is to decrease the moisture level of a predetermined amount of biomass from X percent to Y percent. By organizing assumption, boundaries, and constraints and defining related functions, the problem will be formulated (Kaushik , Preethi , & Gopalkrishna, 2018).

### 4.1.3 Solving the problem

In general, fully understanding the problem, correctly imagining the constraints, being creative, and producing new ideas are necessary for solving problems. Different strategies and analytical methods should be used to find the optimum solution (Sharp, 1991).

Engineering solutions result from engineering designs, which are based on a mixture of technical expertise and innovative technology (Kaushik , Preethi , & Gopalkrishna, 2018). In this project, designing the biomass dryer is the solution for the humid biomass problem.

### 4.1.4 Evaluating the solution

Based on the nature of a problem, engineers normally apply various types of filters to evaluate a solution. There are various indirect methods, which need less budget, for evaluating the products, such as scale models (tiny version of the main design to be tested instead of the main product). Another prevalent way to evaluate a product is to use professional software to simulate the performance of a product on a computer (Summer Institute for Engineering and Technology Education Engineering Design, 1995). In this study, the dryer is designed, and a prototype is constructed to evaluate the design. The prototype is a more simple and less expensive version of the main design that keeps the main features of the main design. The main purpose of the evaluation is to check if the problem remained unsolved or new ones have emerged. The pros and cons of the design are analyzed in order to change the design to a more efficient one. Therefore, the modifying and testing cycle continues to find the desirable design.

## 4.2 Assumptions, boundaries, and constraints

Identifying the assumptions is important for the purpose of determining an effective solution. However, they have different importance and necessity while tackling the problem (Harris, 2002). In this project for instance, algae as a regular type of biomass are tested, and the data extracted from the test are used to do the calculations. Table 4.1 illustrates a list of assumptions, which will be needed for calculations of designing the dryer.

*Table 4.1-Required assumptions (Ragnarsson, 2020)*

| **Assumptions** |
|---|
| m (Total algae) = 50 kg |
| R1 (Algae humidity before drying) = 50% |
| R2 (Algae humidity after drying) = l5% (Ungureanu, Vladut, Voicu, Dinca, & Zabava, 2018) |
| Time of the process = 30 hours |
| X2 (Outlet air) = 11 gram/kg air |
| X1 (Inlet air) = 9 gram/kg air |
| C (Air) = 1.006 (kJ/kg.C) |
| $\rho$ (air) = 1.225 (kg/m3) |
| $L_f$ (Water latent heat at room temperature) = 2260 (kJ/kg) |
| C (Water) = 4.2 (kJ/kg.C) |
| T (Ambient temperature) = 15 °C |

Generally, to stay in the right direction while doing research, it is wise to spend some time scrutinizing and checking the research boundaries. Boundaries are criteria that determine what is relevant and irrelevant to the research. They highlight borders (for the problem, subject, etc.) for researchers to keep them away from the wrong direction (The Thesis Upgrade, 2017). In this project, boundaries can be listed as below:

- The drying cabinet will be designed to dry the biomass. It is not designed for other materials such as nuts or vegetables.
- The drying process will be performed in a cabinet. Other methods for agitating the biomass, such as rotary drum drying, are not the case here.
- The direct drying method for heat transfer is applied in this project.
- Air is the medium used to separate moisture from biomass.

In every design, due to various reasons, designers are limited in some points. These limitations are called constraints. Some of the main constraints in this work are listed below.

- The cabinet should be as compact as possible. The size of the cabinet is a constraint. (Less than 2.5 m in height)

- The budget for this project is limited.
- The nature of the process creates a corrosive environment. Corrosion limits material selection.

## 4.3 Calculations of required heat

For the aim of calculating the amount of required heat for changing the temperature of a certain amount of material, we use the formula explained below:

$$Q = m * C * \Delta T \qquad \textit{Eq. 4.1}$$

Where Q is heat transfer (kJ), m is mass (kg), C is specific heat of material (kJ/kg.°C), and ΔT is temperature change (°C) in material. This formula can be used for calculating the rate of heat transfer (kJ/s) as well, if we substitute mass with mass flow (kg/s) *(Ozisik, 1985)*.

Required heat in a certain amount of material for changing the phase without temperature change can be calculated as below:

$$Q = m * L_f \qquad \textit{Eq. 4.2}$$

Where Q is heat transfer (kJ), m is mass (kg), and $L_f$ is the latent heat of material (kJ/kg). In order to find the rate of heat transfer (kJ/s) we can use mass flow (kg/s) in this formula *(Ozisik, 1985)*.

For calculating the percentage of humidity according to the mass of moisture in the material, this formula can be used:

$$R2 = \frac{(m1 * R1) - m}{m1 - m} \qquad \textit{Eq. 4.3}$$

Where m1 is mass of material before drying (kg), R1 is percentage of humidity before drying, R2 is percentage of humidity after drying, and m is the mass of extra moisture (kg), which is separated in drying process *(Ragnarsson, 2020)*.

Required air flow for dryer can be calculated by this formula, according to absolute humidity, mass of extra moisture, and drying period.

$$F = \frac{\dot{W}}{(X2 - X1)} \qquad \textit{Eq. 4.4}$$

Where F is air flow (kg/s), $\dot{W}$ is rate of water evaporation (kg/s), X2 is absolute humidity of outlet air (kg water/kg air), X1 is absolute humidity of inlet air (kg water/kg air) *(Ragnarsson, 2020)*.

In order to calculate the transferred heat from a certain meterage of a pipe based on inlet and outlet temperature, we can use the formula below:

$$\frac{Q}{t} = 2 * \pi * K * L \frac{T2 - T1}{\ln \frac{r2}{r1}} \qquad \textit{Eq. 4.5}$$

Where Q is heat transfer (J), t is period (s), K is heat transfer coefficient of pipe (W/m.°C), L is length of pipe (m), T2 is water temperature at outlet (°C), T1 is water temperature at inlet (°C), r2 is outer radius of pipe (m), and r1 is inner radius of pipe (m) *(Ozisik, 1985)*.

$$P = \frac{Q}{t} \qquad \textit{Eq. 4.6}$$

Where P is power (W), Q is energy (J), and is period (s) (Ozisik, 1985).

$$MC = \frac{m1}{m} \qquad \textit{Eq. 4.7}$$

Where MC is moisture content of material, m1 is mass of moisture in material (gram), and m is the whole mass of material (gram).

## 4.4 Material selection

Generally, due to the humid weather in Iceland and the corrosive nature of the drying process itself, corrosion is a potential danger for the metallic structure of the design. Consequently, stainless steel is an appropriate selection for this design, although other materials also have been considered to be used.

The punch plates, used in trays, are made of aluminum since aluminum is a suitable material to be used in corrosive environment. Furthermore, aluminum punch plates were more accessible in Iceland rather than other materials. The air distributor is made of PVC. They are widely used in construction works. PVC is cheap, accessible, and easy to be jointed together.

## 4.5 Required equipment

### Dehydrator

In order to perform a drying experiment a household food dehydrator unit was used for drying the material. This device included an electrical element, a fan, and several trays, which were located in a compartment. The power of this dehydrator was 600 W. Figure 4.1 shows the design of the dehydrator.

*Figure 4.1- Food dehydrator*

### Data logger

Six data logger were used to collect data during the long hours of drying tests. Relative humidity, dew point, and temperature were three parameters that can be logged in adjustable periods by loggers. The data can be transferred to a computer at the end of the test in the format of JPG, Excel file or PDF. Figure 4.2 shows the loggers that were used.

*Figure 4.2- Data loggers*

## Moisture meter

We used a mobile moisture meter for measuring the humidity of the seaweed in our experiment. Figure 4.3 shows the moisture meter that we used. This device has two tiny metal bars for sensing the humidity and a screen for showing the percentage of humidity.

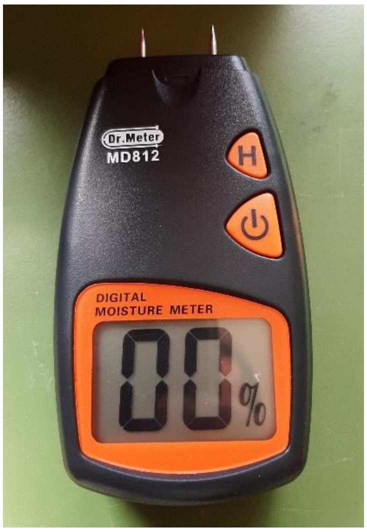


*Figure 4.3- Moisture meter*

## Oven

For the purpose of measuring the moisture content of algae at the end of the tests, we utilized an oven, which can keep the material in a fixed temperature. Figure 4.4 illustrate the oven that we used. It is an insulated compartment, which has 4 trays inside for placing the samples. There are timer, temperature button, and temperature indicator for controlling the test.

*Figure 4.4- Laboratory oven*

## 4.6 Software used in this study

In order to prepare the drawings and 3D models, two engineering software were used. AutoCAD was used to produce primary designs and 2D drawings. AutoCAD is a famous engineering software from Autodesk Inc., which is widely used in the Mechanical Engineering. This software is attractive to engineers because of its friendly user feature. The second software is SOLIDWORKS for producing 3D models. SOLIDWORKS is a professional software for Mechanical Engineering from Dassault Systems.

## 4.7 Chapter summary

This chapter explained the research methodology of the thesis. As mentioned earlier, this project follows a general engineering method for doing a project, which includes problem identification, problem formulation, solving the problem, and evaluating the solution. Some of the main assumptions, boundaries, and constraints in this project were listed in this chapter. In addition, two main engineering software, which helped in the design process, were introduced to the reader. The main objective of this chapter was to explain the applied methods and materials in the project. In the next chapter, required calculations will be presented and the progress of the design will be explained. Furthermore, a preliminary design is presented.

# 5 Calculations, modeling, and creating a preliminary design of the dryer

As it was mentioned in previous chapters, we need to design a biomass dryer to reduce the moisture level in biomass and prepare them for pelletizing and gasification. It is expected to design a machine with a capacity to dry 50 kg of algae in the period of 30 hours. Since this machine is for the purpose of research and has a limited budget, the design is preferred to be regular and not complicated. Therefore, using hot air as a medium to evaporate the moisture and using fewer movable parts in the cabinet can help us to have an inexpensive design. Using sunshine as a free source of heat looks persuasive, however, due to weather conditions in Iceland, we focus on geothermal water or electricity as possible sources of heat for the biomass dryer. Thus, after considering all boundaries, constraints, and assumptions, we formulate the problem and present a design for the dryer as a solution.

In this chapter, the design process is explained. Before creating the first design, an experiment is performed to find the start point. According to the experiment some data are extracted which determines a range for the main parameters of the design. Based on data, extracted from the experiment, some of the major required parameters are calculated. In this chapter, using geothermal water as a heat source for the dryer is considered. The biomass drying cabinet with and without a heat recovery system will be explained as well. The design process from the first model to the final one will be described in this chapter.

## 5.1 Required energy for drying

There are various methods to calculate or estimate the amount of required heat for the purpose of drying 50 kg of algae in particular conditions. Using theoretical formulas, simulating the process in the software, doing experiments, etc. are reliable methods to find the required heat. In the following parts, we work on possible methods to calculate this number.

### 5.1.1 Drying experiment

Before beginning to design the cabinet, a drying test was done to collect some data such as drying time, moisture content, density, etc. To begin with, a half-liter volume of algae, which was collected from Ægissíða beach in Reykjavík was considered as the sample for drying. Figure 5.1 shows grown algae on the beach. The food dehydrator, which was explained in previous chapter, was used in this experiment. Half liter algae were shredded before drying. Then, the mass and humidity were measured. The drying process lasted for 70 minutes.

*Figure 5.1- Ægissíða beach*

Table 5.1 presents all the extracted data and some of the calculated parameters from the experiment. Row number 6 records the amount of moisture which was separated from the algae. According to this value, the required heat for changing the temperature from 10 °C (room temperature) to 30 °C (dryer outlet air temperature) has been calculated in row number 7. As we see in row number 8, the required heat for evaporating the separated moisture has been calculated. In row number 9, the value of the total energy consumption over the course of 70 minutes is provided. On the one hand, according to calculations, we need Q1+Q2 (5.9kJ+158.2kJ) to dry 140 grams of algae. On the other hand, according to the experiment, we have consumed Q (2520 kJ) during experiment. The difference between these two numbers depicts the amount of heat loss and fan electricity consumption during the experiment; the total of which is Q3. Consequently, we can conclude that almost 93% of the total consumed energy in a drying process is due to both the heat loss, and the energy required to power the fan.

*Table 5.1-Data extracted from experiment*

| No. | Parameter | Quantity | Explanation |
|---|---|---|---|
| 1 | Mass (wet algae) (kg) | 0.14 | Measured by scale before process |
| 2 | Mass (dry algae) (kg) | 0.07 | Measured by scale after drying |
| 3 | Process time (s) | 4200 | 70 minutes |
| 4 | Humidity before drying | 50% | Measured by moisture meter |
| 5 | Humidity after drying | 18% | Measured by moisture meter |
| 6 | Mass of extra moisture (kg) | 0.07 | Mass (wet algae) – Mass (dry algae) |
| 7 | Q1=Required energy for heating algae (kJ) | 5.9 | Eq. 4.1: $Q1= m*C(water)*(T2-T1)$<br>$Q1=0.07(kg)*4.2(kJ/kg.C)*(30-10)(C)$ |
| 8 | Q2=Required energy for moisture evaporation (kJ) | 158.2 | Eq. 4.2: $Q2= m*L_f$(water latent heat)<br>$Q2=0.07(kg)*2260(kJ/kg)$ |
| 9 | Q=Total energy consumption (kJ) | 2520 | Dryer power = 600 W<br>$Q=600*4200$ |
| 10 | Q3= Heat loss (kJ) + Fan consumption(kJ) | 2356 | $Q3 = 2520-5.9-158.2$<br>Q3=93% of Q |

### 5.1.2 A rough estimate of required energy

Table 5.2 presents calculations based on an estimation according to the experiment, which was explained in the previous section. As we see in the table, the assumed capacities such as mass and humidity have been mentioned here. In row number 4, the amount of extra moisture in 50 kg of algae has been calculated. According to this value, the required heat for changing the temperature from 10 °C (room temperature) to 30 °C (dryer outlet air temperature) has been calculated in row number 5. As we see in row number 6, the required heat for evaporating separated moisture has been calculated. In row number 7, Q3, which is a summation of heat loss during the drying process as well as fan energy consumption, has been estimated, based on the percentage (93%) that we estimated in previous section. Finally, in the last row, the total energy consumption has been calculated, based on the estimation of heat loss and fan energy consumption.

*Table 5.2- Estimation of required total energy according to the mass of algae and data from experiment*

| No. | Parameter | Quantity | Explanation |
|---|---|---|---|
| 1 | m1=Mass (wet algae) (kg) | 50 | Capacity of the dryer |
| 2 | R1=Humidity before drying | 50% | Assumption |
| 3 | R2=Humidity after drying | 15% | Assumption |
| 4 | m=Extra moisture (kg) | 20.6 | Eq. 4.3: $R2 = \frac{(m1*R1)-m}{m1-m}$<br>$0.15 = \frac{(50*0.5)-m}{50-m}$ |
| 5 | Q1=Required energy for heating algae (kJ) | 1730 | Eq. 4.1**Error! Reference source not found.**: Q1= m∗C(water)∗(T2-T1)<br>Q1=20.6(kg)∗4.2(kJ/kg.C)∗(30-10)(°C) |
| 6 | Q2=Required energy for moisture evaporation (kJ) | 46560 | Eq. 4.2: Q2= m∗$L_f$(water latent heat)<br>Q2=20.6(kg)∗2260(kJ/kg) |
| 7 | Q3= Heat loss (kJ) + Fan consumption(kJ) | 689860 | Q3=((Q1+Q2)/(1-0.93))∗0.93 |
| 8 | Q=Total energy consumption (kJ) | 738147 | Q=Q1+Q2+Q3 |

According to the approximate estimation, which was concluded from the experiment in the previous section, 738 MJ of energy is required to reduce the moisture level of 50 kg of algae from 50% to 15% in a drying process.

## 5.2 Required airflow

In order to create a direct contact between air and algae to alleviate heat transfer and also replace the high humid air with fresh air, a fan can be applied. According to the formula, mentioned below, we can calculate suitable airflow for the drying process.

$\dot{W}$ (rate of water evaporation) = m/t

t (time of process) = 30 hour

$\dot{W}$= 20.6 kg/ 30 hour = 0.69 kg/h

$$\text{Eq. 4.4:} F = \frac{\dot{W}}{(X2 - X1)}$$

X2= absolute humidity of outlet air = 11 gram/kg air

X1= absolute humidity of inlet air = 9 gram / kg air

Fan flow= $F = \frac{0.69}{(0.011-0.009)}$ = 345 kg (air)/hour= 282 $m^3$/h = 166 cfm

$$\text{Eq. 4.6: } P = \frac{Q}{t}$$

P(power) = $\frac{Q}{t}$ = 738147 kJ/30 hours = 6.8 kW

According to these calculations, we need a fan with 166 cfm capacity. In addition, we need 738 MJ energy for drying 50 kg of algae in 30 hours. In other words, based on power definition, we need 6.8 kW power to dry 50 kg algae.

## 5.3 Considering hot water as a source of heat for the dryer

In Iceland geothermal water is a source of safe and cheap energy, which is available all over the country. In other countries without access to the geothermal water, hot water from central heating system or any other sources can be used. Therefore, in this section we are considering hot water as a heating source for drying biomass. Before creating the design, we need to calculate what meterage of the pipe and how much hot water flow we need for transferring the required heat to biomass.

### 5.3.1 Pipe length and hot water flow

We estimated before that we totally need 652971 kJ energy for drying 50 kg of algae. Here For the purpose of finding the required flow and pipe length, we assume that we need 652971 kJ heat in 30 hours. To calculate the required flow for hot water, we can use equation 4.1.

$$\text{Eq. 4.1: } Q = m * c_p * (\text{Tin} - \text{Tout})$$

Q = 738147 kJ

738147 kJ = m ∗ 4.2 (kJ/kg.˚C) ∗ (70 – 60)°C

m (required mass of hot water) = 17575 kg = 17630 liter

ṁ (required mass flow of hot water) = 17630 liter / 30 hours = 0.163 kg/s = 0.163 l/s

Required pipe:

Eq. 4.5: $\frac{Q}{t} = 2 * \pi * K * L \frac{T2 - T1}{\ln\frac{r2}{r1}}$

K = heat transfer coefficient of purchased pipe = 0.4 w/m.k

T2= inlet water = 70 ˚C

T1 = outlet water = 60 ˚C

r2 = outer radius of pipe = 11.125 mm

r1= inner radius of pipe = 10 mm

$$\frac{738147\ kJ}{30\ hours} = 2 * \pi * 0.0004 \frac{W}{m.K} * L \frac{70 - 60}{\ln\frac{11.125}{10}}$$

L (Required length) = 28.8 m

According to the calculations above, in the case of using hot water as a heat source for drying 50 kg of algae, we need 28.8 meter of pipe to transfer heat, while the flow rate of water inside the pipe needs to be 0.162 l/s. The inlet and outlet temperature of heating water should be 70 °C and 60 °C, respectively.

### 5.3.2 Biomass drying cabinet design with hot water heating

Figure 5.2 shows a predesign for the cabinet. As we see in the drawing, the cabinet is separated by a plate to an area for biomass and another space for heating pipes. There is also a separate fan to circulate the air inside the cabinet. Fresh air enters the cabinet by fan and receive heat from hot water piping system, then goes through materials from the bottom of cabinet to evaporate the extra moisture. In Figure 5.2, the flow of air can be checked.

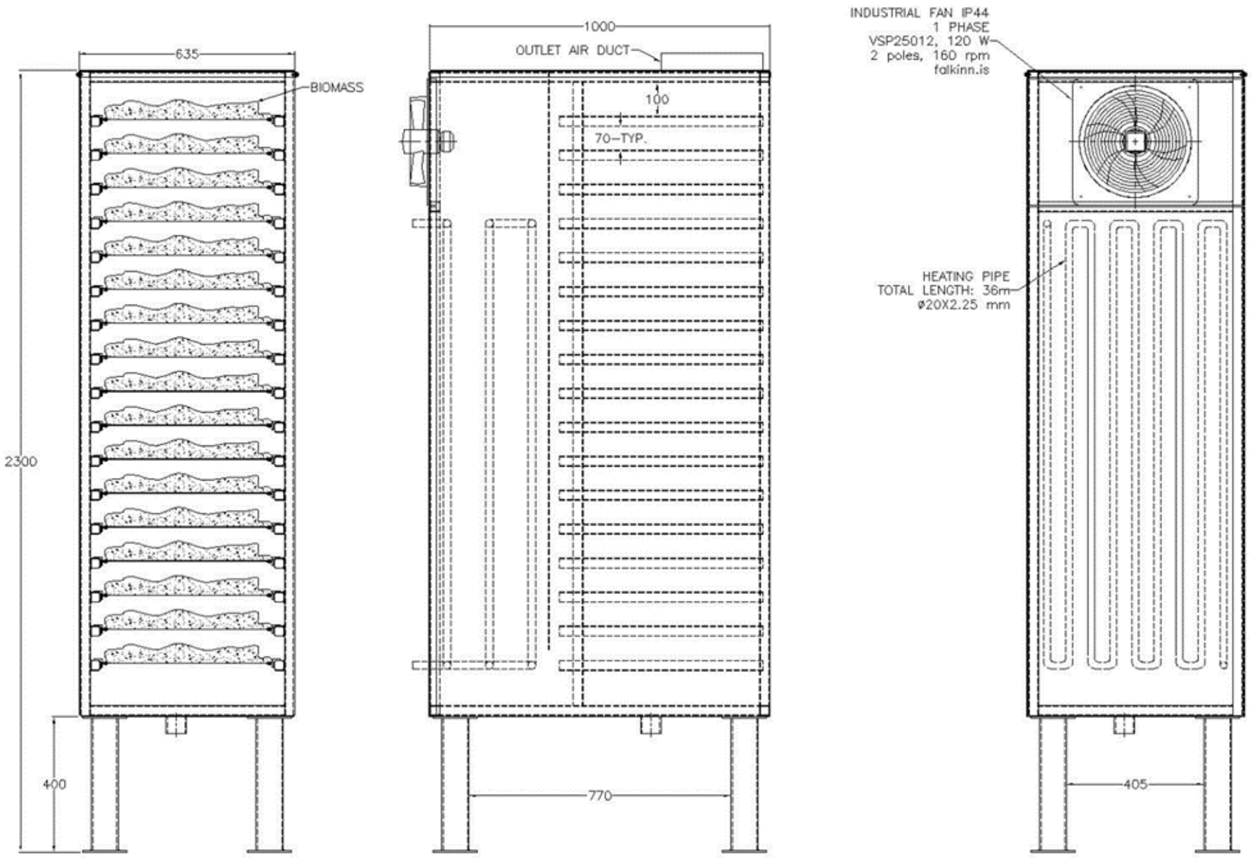


*Figure 5.2-Biomass drying cabinet with hot water heating*

### 5.3.3 Hot water heating disadvantages

While the hot water heating design uses hot water energy for drying biomass and looks like an efficient design, it has some disadvantages that encourage us to search for more appropriate designs. Having access to hot water is the first barrier that limits suitable locations for running the dryer. Second, the hot water heating dryer is spacious. Third, piping is expensive and needs regular maintenance. Although hot water is widely available in Iceland, we decided to use an electric heating system, which is explained in the next section.

## 5.4 Biomass drying cabinet design using electric heating

According to our discussion about the disadvantages of the hot water heating design and considering both possible heating options (hot water heating and electric heating), we decided to use an electric heater in the cabinet. After checking available heaters in the market, a 9-kW heater with 980 cubic meter per hour airflow was chosen. Figure 5.3 shows the chosen heater for the biomass drying cabinet. This heater consists of heating elements, fan, control panel, cylindrical body (made of steel), metal base, 3 phase electric wire.

The use of an electric heater provides a more compact design as well as solves the problem of needing geothermal water accessibility. In the next design, the electric heater has been used. Figure 5.4 illustrates the cabinet with the electric heater at the bottom. As it is shown in 3D view, warm air is pumped to the cabinet from the bottom and humid air leaves the cabinet from the top. The cabinet in this design is smaller than the previous one since there is no geothermal water piping inside the cabinet.

*Figure 5.3-Electric heater*

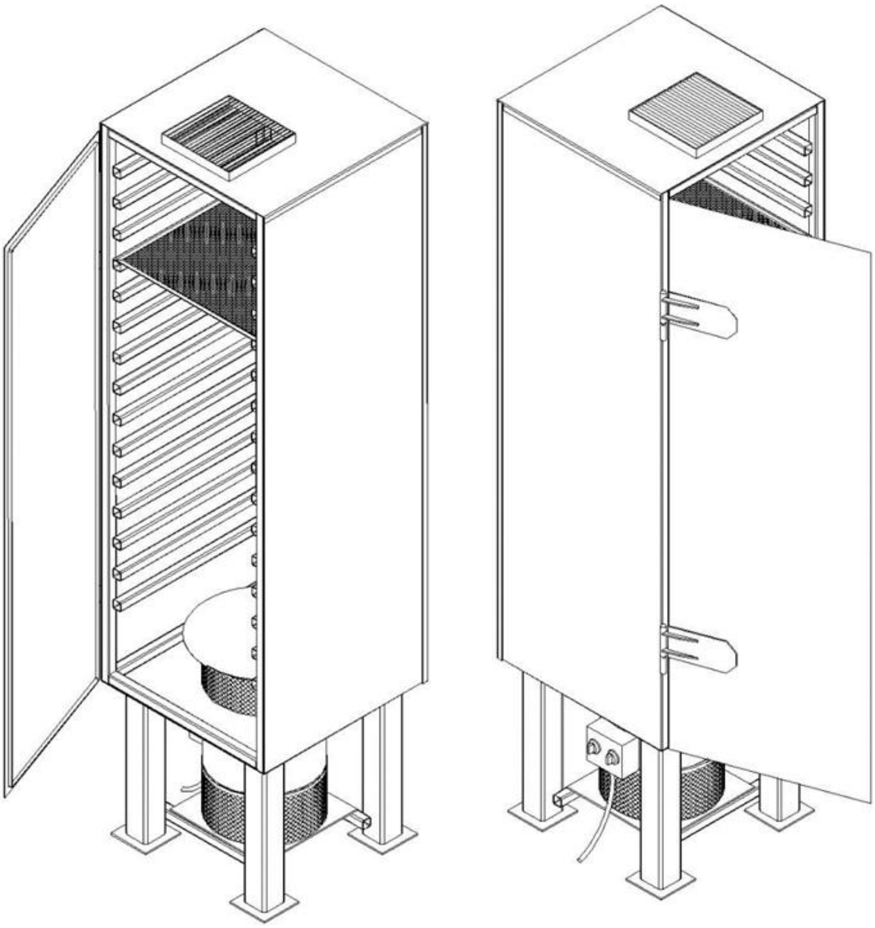


*Figure 5.4-Biomass drying cabinet with electric heater*

## 5.5 **Adding an energy recovery cycle to the system**

In order to improve the efficiency of the system and reuse the heat, an air circuit is added to the cabinet to send back the warm air to the entry. Figure 5.5 is a primary design, which shows how new components are arranged in the heat recovery cycle. According to this design, a dehumidifying box has been added to the system to separate the extra moisture from the air. This box consists of a dehumidifier, baffle plates, and a drain. Baffle plates are located inside the box to capture the floating droplets in the air and separate them from the system through the drain. Flexible pipes, which have insulation features, are used to connect components. This design will improve to a more compact one and a better arrangement in the next section.

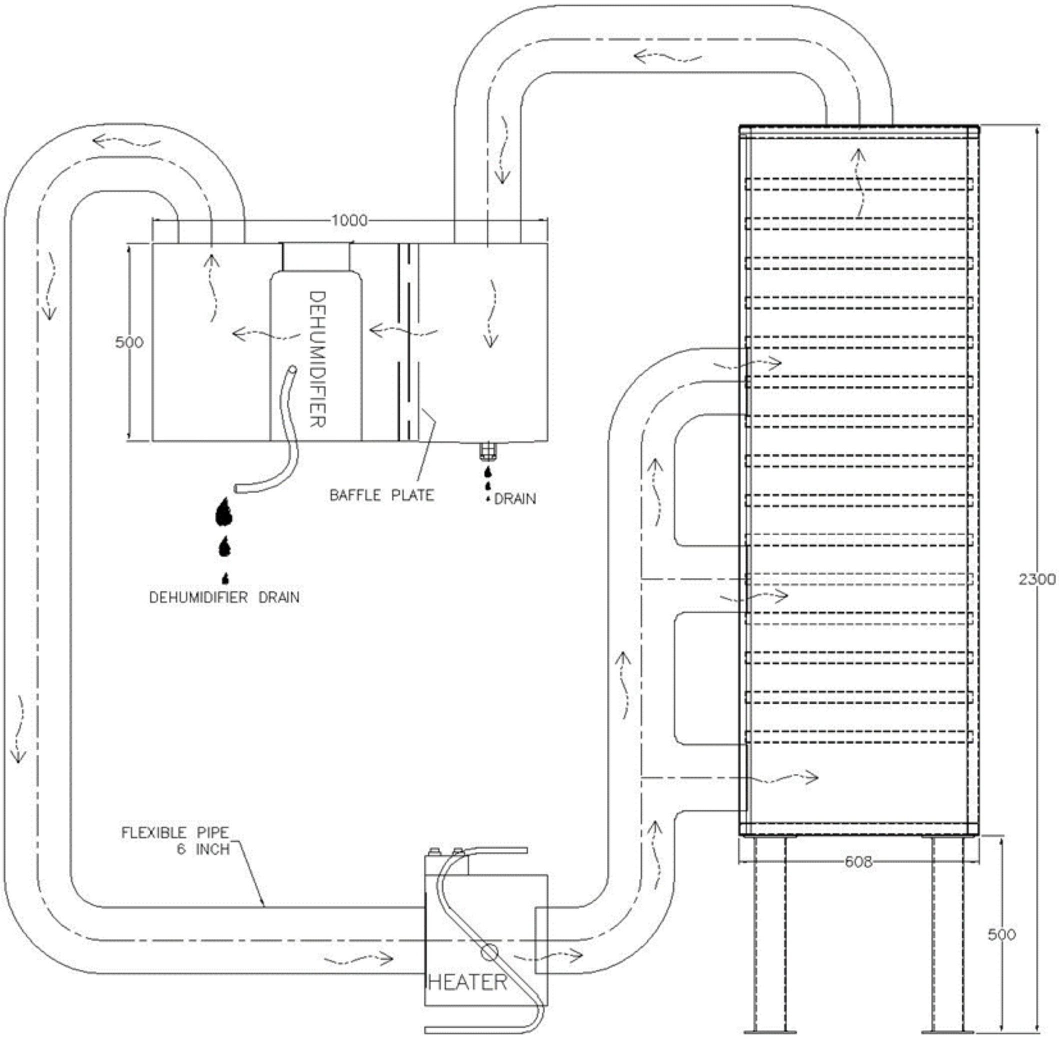


*Figure 5.5-Biomass drying cabinet with heat recovery system*

The dehumidifier is a separate unit, which was purchased, to capture the rest of the moisture using the condensation method. Figure 5.6 shows the dehumidifier unit. This unit has 230 W input power and 0.41 liter per hour capacity. A regular refrigeration circuit (compressor, condenser, expansion valve, and evaporator) is applied to condense and separate the existing moisture in the air. Copper pipes, covered by blue fins, illustrate the condenser part in this unit.

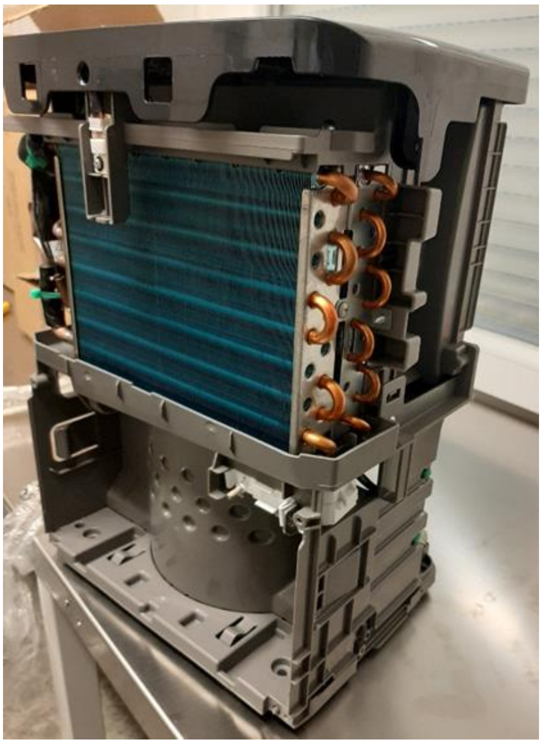


*Figure 5.6-Dehumidifier*

## 5.6 Preliminary design

This design for the biomass drying cabinet is basically similar to the previous one, which was presented in previous section. In the preliminary design, the components are in a less spacious arrangement. Figure 5.7 shows a drawing with two views of this design. As we see in the left view, the dehumidifying box and the heater are placed on the left side of the cabinet. The dehumidifying box is fastened to the upper part and is connected to the cabinet throughout a 130 mm hole. In the lower part, we can see the heater. It is connected to the dehumidifying box and the air distributor duct through a five-inch flexible pipe. The air distributor is a five-inch PVC pipe, which distributes the warm air through 3-inch pipes into the cabinet. The cabinet has 15 trays, which are used to keep 50 kg of biomass on them. Figure 5.8 illustrates the tray. The arrows show how warm air passes through the biomass.

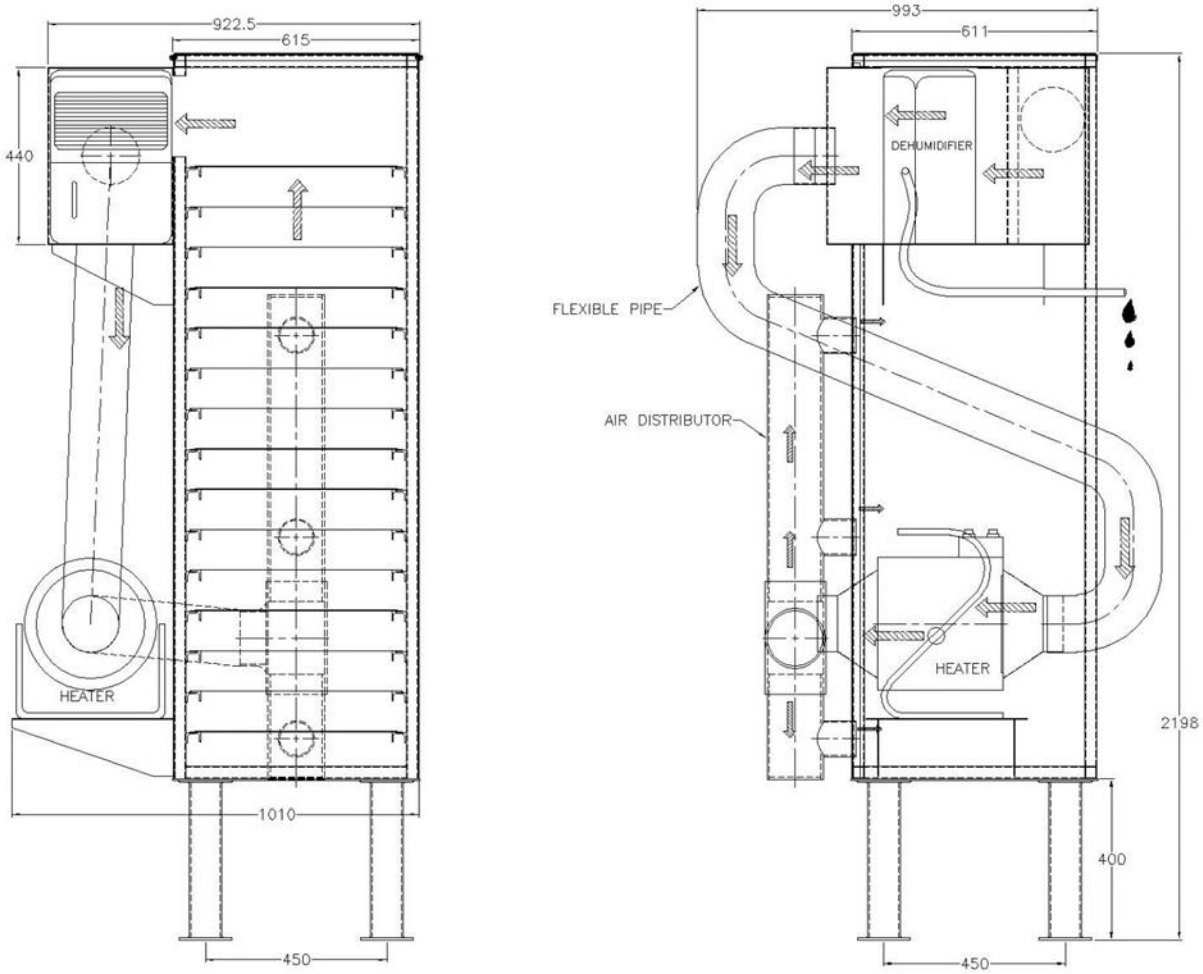


*Figure 5.7-Preliminary design of biomass drying cabinet with the heat recovery system*

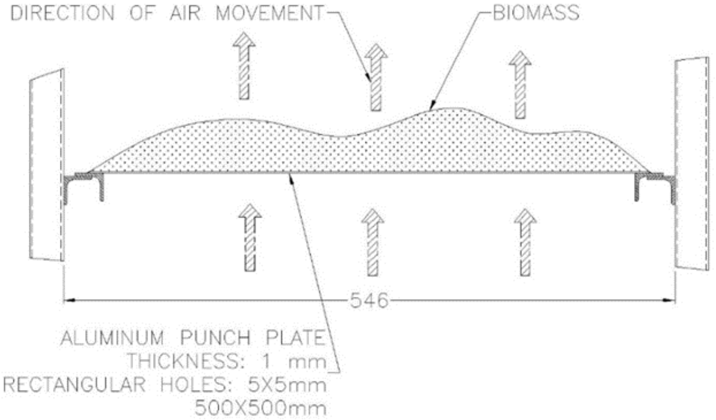


*Figure 5.8-A tray of the cabinet*

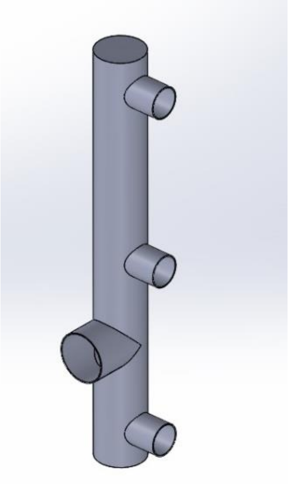


*Figure 5.9- Air distributor*

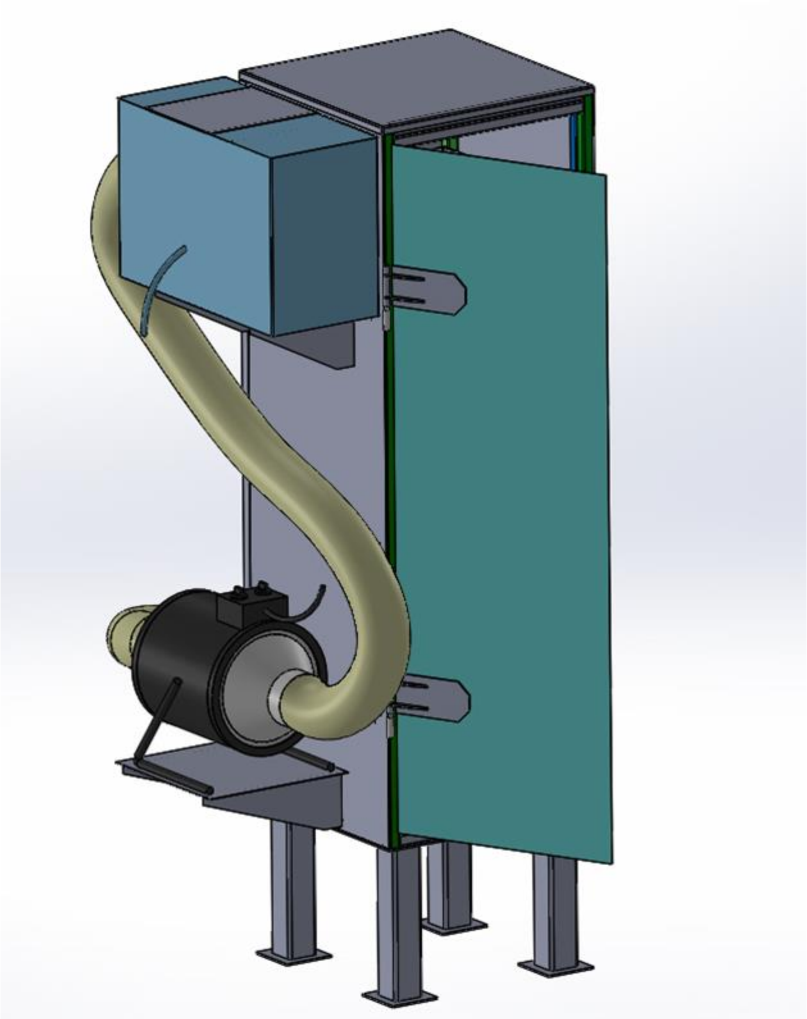


*Figure 5.10- A 3D model of the preliminary design*

Figure 5.9 illustrate a 3D model of air distributor. This duct is made of a 140 mm long five-inch PVC pipe and three pieces of three-inch pipe, which are jointed to the main pipe in every 0.5 m. Through this design we can distribute air flow better in three different places of the cabinet. *Figure 5.10* shows a 3D model of the design. Dehumidifying box, electric heater, flexible pipes, and the cabinet are illustrated in this picture.

## 5.7 **Chapter summary**

The design process of the biomass drying cabinet was explained step by step in this chapter. In order to find some of the required data for calculations, a small-scale experiment of algae drying was performed. In the first design, hot water was used as a heating source. However, an electric heater replaced that in the second design. As it was shown, a heat recovery cycle was added to the cabinet to reuse heat and send warm air back to the cabinet. Therefore, a dehumidifier was added to the system to separate and remove extra moisture from the air and reuse the warm air. The preliminary design was equipped with a heat recovery system. In the next chapter, a prototype of the preliminary design will be constructed and tested to evaluate its performance.

# 6 Prototype construction, testing and evaluating the preliminary design

In the previous chapter, a preliminary design was presented. In order to test and evaluate the design, a prototype of the preliminary design is presented in this chapter. In this design stainless-steel sheets were replaced with wooden panels (Figure 6.1- Wooden cabinet with metal frame), the tray design was simplified, the condenser box was replaced with a plastic container, and the cabinet door was replaced with a temporary plastic sheet. Figure 6.2 shows a view of the dryer. This prototype is presented as an early sample of the biomass drying cabinet to keep the project within budget. Despite applying inexpensive parts with different materials, the prototype keeps the basic concepts of the biomass drying cabinet. The cabinet has a 2-meter height, half-meter length, and half-meter width. There are 15 trays (48cm x 48cm) inside the cabinet.

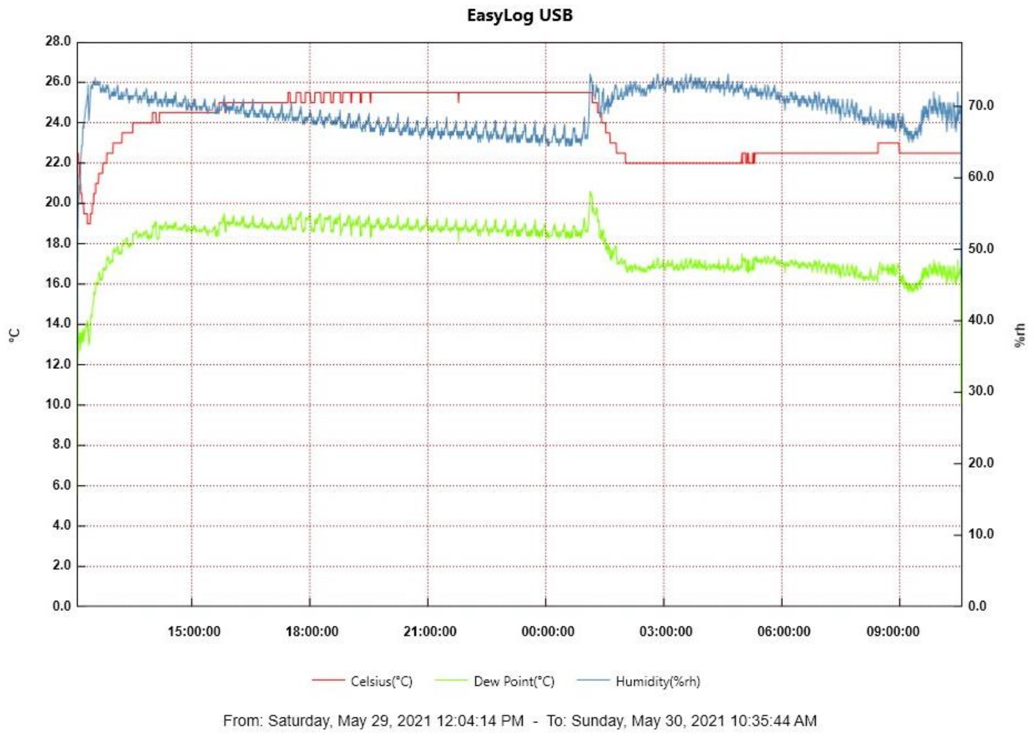
*Figure 6.1- Wooden cabinet with metal frame*

As we see in Figure 6.2, the transparent plastic container plays the role of the condensation box in the preliminary design. The dehumidifier is located inside the transparent box. The outlet air from the cabinet is supposed to lose moisture while passing through the transparent plastic container. Then the warm air with less moisture enters the heater and goes back to the cabinet to repeat the cycle.

*Figure 6.2- Prototype of the dryer with the heat recovery system*

## 6.1 **Testing the prototype**

After the construction process, we test the prototype and present the results in this section. Figure 6.3 shows the changes in temperature, relative humidity, and dew point inside the cabinet during 23 hours of drying test. The logger was placed on a tray at the middle of the cabinet. It should be mentioned that at the end of the test the connection between the heater and the cabinet was broken. According to the graph, we can estimate that the connection was broken 13 hours after the beginning of the test. By analyzing the graph, we can conclude that the whole system is not working properly. The performance of the dryer is discussed in the next section.



From: Saturday, May 29, 2021 12:04:14 PM - To: Sunday, May 30, 2021 10:35:44 AM

*Figure 6.3- Temperature, relative humidity, and dew point graph during the test of the prototype*

## 6.2 Why the results were unacceptable

According to the graph, the temperature goes up first and stay constant at 26 °C for the first 13 hours (We do not consider the results after 13 hours (1:00 AM) since the connection had failed and the results are invalid.). In addition, the relative humidity of the air inside the cabinet does not reduce properly during the test. Considering these results, we can conclude that the heat recovery system is not responding due to the reasons listed below:

- The dehumidifier unit inside the plastic container is not separating the moisture from the air because the performance of the dehumidifier was disrupted in a limited space (the plastic container). On the other hand, the dehumidifier unit, despite what is stated in the catalog, is not powerful enough to separate that amount of moisture from the air.
- The heater is composed of a fan and elements. The elements turn off when the inlet air is warm. In other words, if we want to use this heater for the heat recovery cycle, we should adjust the on and off temperature of the heater to higher degrees. Therefore, the heater during the test was not working continuously and the inlet air was not warm enough during the test.

## 6.3 **Prototype revision**

After considering the results of the test we reconsider the heat recovery system. The heat recovery system in our project, due to some reasons, is not necessary. First, in Iceland, unlike other countries, electricity is not expensive, and this drier is not designed to work continuously. Consequently, we do not have to pay too much for electricity. Second, the relative humidity of the air in Reykjavik often is not extremely humid and we can use ambient air for the drying process. Furthermore, for modifying the heat recovery system we need to buy a more powerful dehumidifier and change the settings of the heater, which is very expensive. Generally, installation, and maintenance of the dryer with heat recovery system is costly. Consequently, we decided to eliminate the heat recovery cycle in this study and use ambient air for the drying process. Figure 6.4 illustrates the revised dryer.

*Figure 6.4- The prototype of the dryer without heat recovery cycle*

## 6.4 **Chapter summary**

In this chapter, a prototype of the preliminary design of the dryer was introduced and tested. According to the results of the test, it was agreed to eliminate the heat recovery system and revise the prototype. The next chapter is dedicated to the tests and evaluation of the revised dryer.

# 7 Drying test, result analysis, and design evaluation

In this chapter, we test the prototype of the dryer, which was revised in the previous chapter, and check its performance. During the tests, all important parameters like time, temperature, and humidity reduction are logged and presented here.

## 7.1 Temperature and relative humidity

The next stage of this study is evaluating the design. A simplified model for the designed dryer was constructed and illustrated in the previous chapter. After construction, several drying tests are performed with this dryer and the results are presented in the following parts. The main test is 49 hours drying test. It was supposed to be long enough to produce steady-state humidity and temperature curves. The temperature and relative humidity inside the cabinet were logged every minute during the test. Loggers were placed on the top shelf, middle shelf, bottom shelf, inside the inlet duct, inside the outlet duct, and outside of the cabinet. Totally, six loggers were applied to log the required parameters during 49 hours of the drying process. Table 7.1 shows some of the main parameters of the test.

*Table 7.1- Test condition*

| No. | Parameter | Quantity | Explanation |
|---|---|---|---|
| **1** | Mass (wet algae) (kg) | 4.5 | Batch of algae |
| **2** | Room temperature (°C) | 23 | Dryer place |
| **3** | Heater power (kW) | 9 | Maximum power of the heater |
| **4** | Air flow ($m^3/h$) | 980 | Maximum air flow of heater |

### 7.1.1 Data analysis inside the cabinet

Figures 7.1 compares the changes in temperature inside the cabinet during the test. Considering all curves together, we witness that temperature goes up to a certain level in the first 10 or 15 hours, then remain constant till the end of the test. According to the graph, we have maximum average temperature in the bottom shelf and minimum average temperature in the top shelf. Figure 7.2 compares relative humidity in three different places inside the cabinet. As we witness in the graph the relative humidity decreases constantly during the first few hours and stabilizes later. Consequently, we can conclude that the inlet air and algae achieve a balance in humidity when the humidity curve stabilizes. In other words, the drying aim is accomplished, when the relative humidity stays constant. According to the results, algae at bottom shelves dry faster than algae at top shelves since warm air is blown from the bottom and exits from the top. The capability of warm air for absorbing moisture reduces while going up inside the cabinet. The averages of temperatures in different points inside the cabinet are not similar. The average temperature at the bottom shelf, close to the inlet air duct, is 49 °C, at the middle shelf is 44 °C, and at the top shelf is 41 °C.

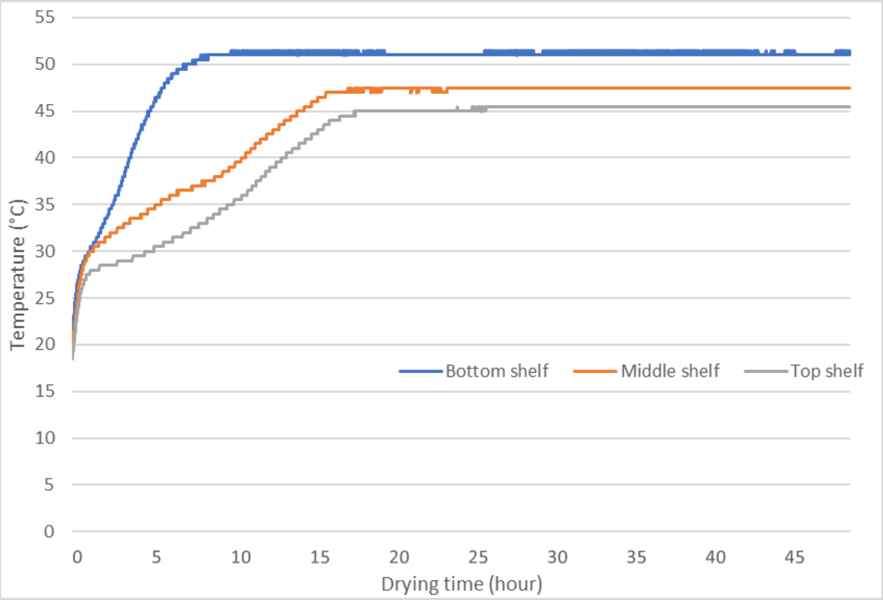


*Figure 7.1- Comparison of temperature changes inside the cabinet*

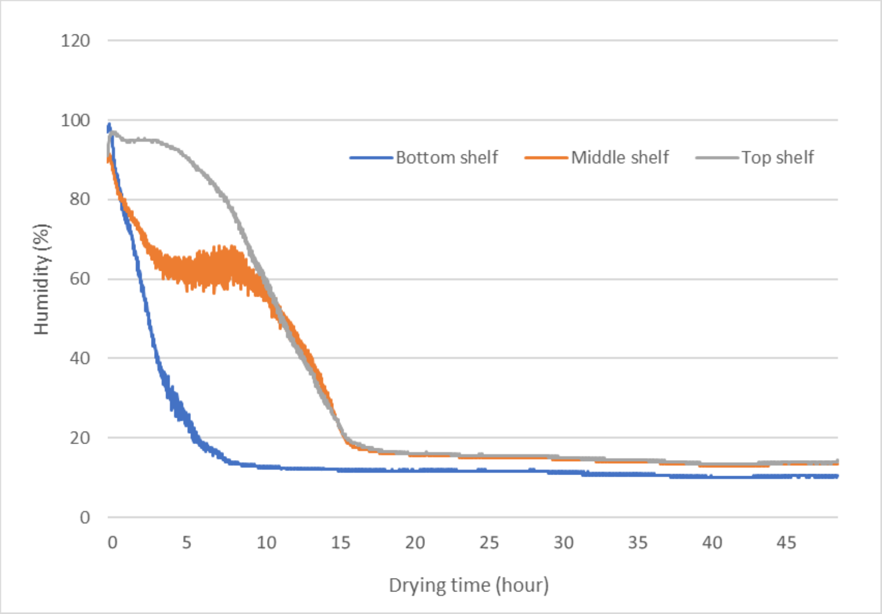


*Figure 7.2- Comparison of humidity changes inside the cabinet*

### 7.1.2 Data analysis related to inlet air, outlet air, and outside of the cabinet.

Figure 7.3 compares temperature changes in inlet and outlet ducts. According to this graph, the average temperature in inlet duct is higher and the temperature in inlet duct stabilizes faster. The average temperature of the inlet air is 59 °C, while it is 43 °C in the outlet. Figure 7.4 compares the relative humidity in inlet and outlet duct. According to this graph, the relative humidity decreases to a certain level in the first few hours, then remains constant till the end of the test. Not surprisingly, relative humidity in outlet duct is higher than inlet duct. The average temperature in the room during the experiment increased from 23 °C to 29 °C. Due to heat loss from the cabinet and heater, the room temperature gently increases. Consequently, relative humidity of the room decreases since the capacity of air for solving moisture rises when the temperature goes up. Figure 7.5 shows the appearance of algae before and after 49 hours of drying.

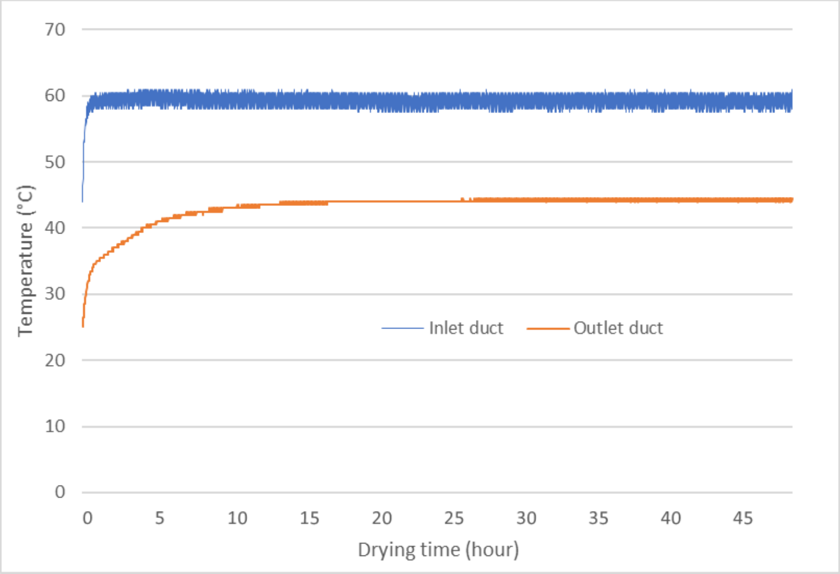


*Figure 7.3- Comparing temperature in inlet and outlet duct*

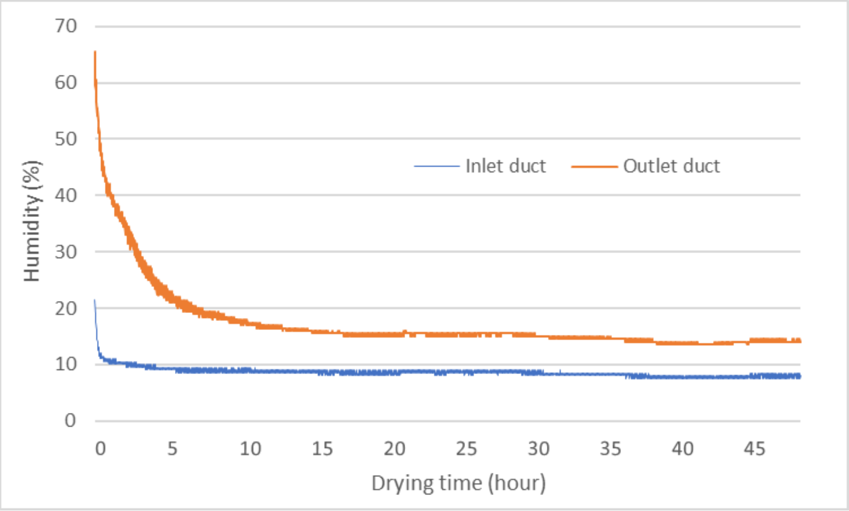


*Figure 7.4- Comparing humidity in inlet and outlet duct*

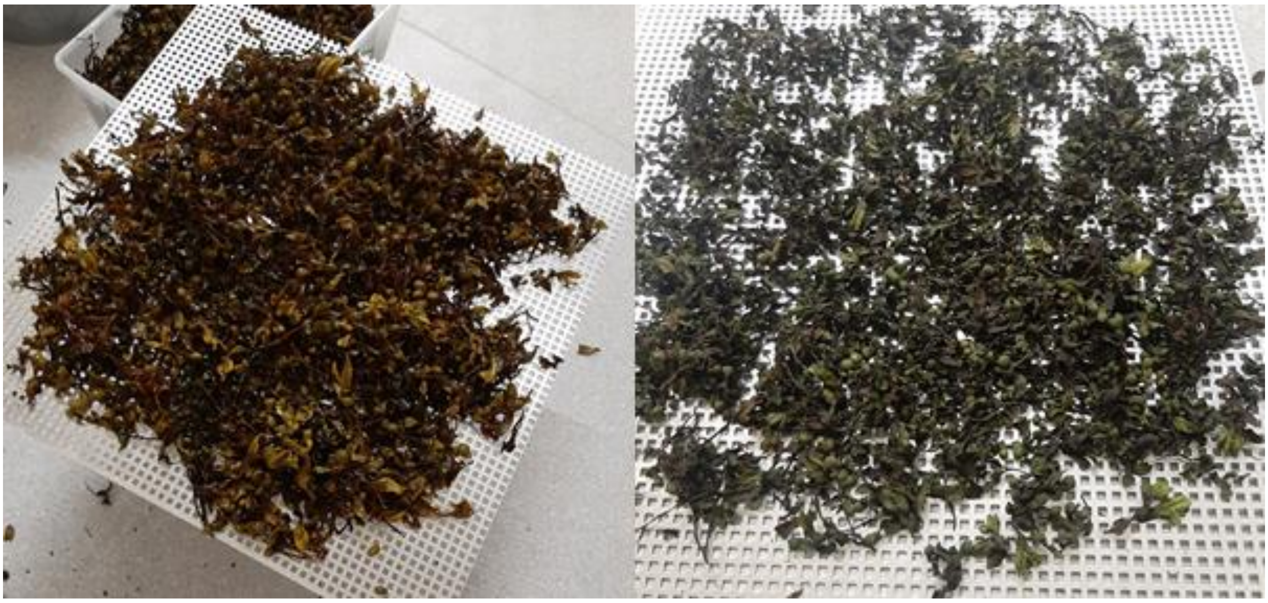


*Figure 7.5- Appearance of algae before and after drying*

## 7.2 **Moisture content determination**

After drying 4.5 kg algae in a 49-hour test, the leftover algae are 1.081 kg. As we discussed before, it is a goal to have final material with less than 20% moisture content. In this part, we determine the moisture content of the leftover material to check if we reached the goal of drying or not. We utilized the oven (described in chapter four) to heat up the algae for three hours in 105 °C. In oven drying method according to EN ISO 18134-2, we weigh the algae and put it in the oven at 105 °C for some hours to be sure that material is completely dry. We decided to wait for three hours. (Mendel, Überreiter, & Kuptz, 2016). After three hours we take out the samples and weigh it again. In this experiment, I used six samples, and each sample was 60 grams. Figure 7.6 shows samples before and after drying. Table 7.2 presents weight loss and moisture content of samples as well as relevant average number for each parameter. Equation 4.7 was used to calculate the moisture content of material.

$$\text{Eq. 4.7: MC} = \frac{m1}{m}$$

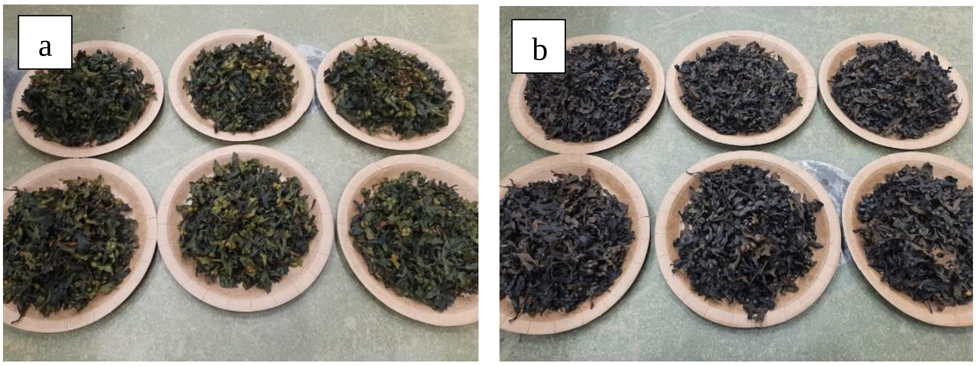


*Figure 7.6.a- Samples before oven drying, b- Samples after oven drying*

*Table 7.2- Weight loss and moisture content determination of 6 samples, which were dried for 49 hours (Mendel, Überreiter, & Kuptz, 2016)*

| | **Sample1** | **Sample2** | **Sample3** | **Sample4** | **Sample5** | **Sample6** | **Average** |
|---|---|---|---|---|---|---|---|
| **Mass before drying (gr)** | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| **Mass after drying (gr)** | 53 | 55 | 54 | 53 | 53 | 54 | 53.7 |
| **Weight Loss (gr)** | 7 | 5 | 6 | 7 | 7 | 6 | 6.3 |
| **Moisture Content** | 11.7% | 8.3% | 10% | 11.7% | 11.7% | 10% | 10.6% |

## 7.3 Moisture content of algae over time

In the previous part, the results of a 49-hours test were explained. In order to not interfere with the test, we did not measure the mass of the algae during the test. Consequently, we decided to run several shorter tests with similar conditions so as to achieve the mass of the algae at different times from the start of the test. Five more tests with different drying times were done and for all the tests 4.5 kg of algae were dried. The mass of algae was measured before and after each test. Table 7.3 illustrates the mass and moisture content of algae of algae in 6 different tests.

*Table 7.3- Mass and moisture content of algae in 6 different tests*

| | Mass before drying (gr) | Mass after drying (gr) | Moisture content |
|---|---|---|---|
| **Before drying** | 4500 | - | 78.5% |
| **2 hours test** | 4500 | 3215 | 69.9% |
| **4 hours test** | 4500 | 2557 | 62.2% |
| **6 hours test** | 4500 | 1882 | 48.6% |
| **14 hours test** | 4500 | 1488 | 35% |
| **22 hours test** | 4500 | 1095 | 11.7% |
| **49 hours test** | 4500 | 1081 | 10.6% |

In Figure 7.7 the vertical axis shows the moisture content of algae in seven different times from the beginning of the test, and the horizontal axis shows the hours passed from the beginning of the process. The red points show the data extracted from the tests and the trendline, which is fitted to the data points, shows the trend of the drying process. The trendline has been drawn based on an inverse equation ($Y=\frac{Ax+B}{Cx^2+Dx+E}$).

In this equation: A=370, B=800, C=0.8, D=0.5, E=4

Each red point represents the moisture content of algae in a period from the beginning of the test. For each point, an error bar based on different measurements has been applied to indicate the error or uncertainty of the test. Red point is the median point among three measurements for each test.

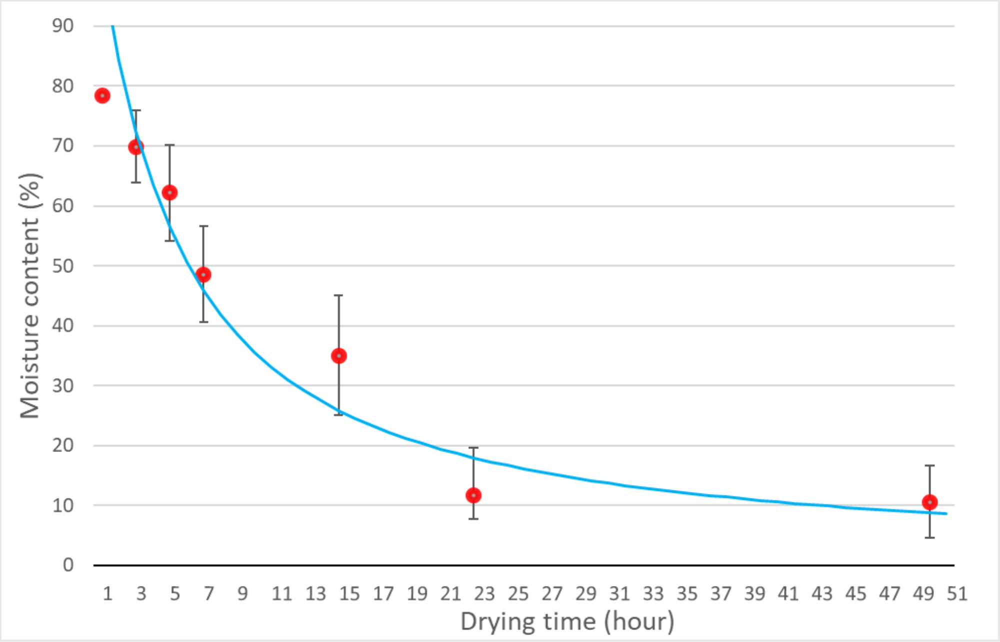


*Figure 7.7- Moisture content of the algae during 49-hours of drying test*

According to the results of the tests, shown above, mass reduction in algae is more than 50% in the first 6 hours of the test. In other words, the maximum drying rate happens at the beginning of the test, and it gradually reduces over time. We witness that the drying rate obviously reduces after 6 hours. Not surprisingly, we see the maximum moisture separation in the first 2 hours. That is to say, the maximum drying rate happens in the first two hours. The moisture content of fresh algae, before any drying process is 78.5%. The moisture content of algae after 14 hours from the beginning of the test reduces to 35%, and then reduces more to 11.7% after 22 hours. When we compare the moisture content of algae in 22 hours and 49 hours, we see that the moisture separation has almost stopped, and the drying rate is close to zero. Consequently, the goal of the project, which was reducing the moisture content of algae to less than 20%, has been achieved after 22 hours of drying.

## 7.4 **Analyzing and evaluating the results of the tests**

In chapter five we presented a preliminary design, which was equipped with the heat recovery system. We constructed a prototype of the preliminary design. The prototype was tested, and the results were unacceptable. Thus, we decided to remove the heat recovery cycle. Generally, using the heat recovery system can reduce heat loss and make the dryer more efficient. However, in Iceland, due to easy access to cheap electricity and low humid ambient air, reusing the warm air might not be as economical as other places in the world. Furthermore, the cost of installation and maintenance of the heat recovery system in Iceland is very high. Consequently, we decided to eliminate the heat recovery system in the prototype. Totally, the results of the tests reveal that the dryer design without a heat recovery system was successful, and this design can be considered as a practical solution for the humid algae problem. Some of main points about this design are explained below:

- By focusing on the results of the two longest tests in Table 7.3, it is observed that the mass of dry algae has not changed considerably from 22 hours to 49 hours of drying. The moisture content of algae after 49 hours reduces to 10.6%, while it was 11.7% after 22 hours. Just 1.1% reduction in moisture content happened in 27 hours (22-49 hours). We can conclude that the desirable moisture content (less than 20%) has been achieved after 22 hours in the current thermodynamical conditions (temperature, relative humidity, pressure, etc.). According to the blue curve in Figure 7.7, we can reduce the moisture content of algae to 15% within 30 hours. Consequently, the research question has been answered, and the problem of high moisture level in biomass has been solved by this design.
- For the aim of doing the tests, we intended to construct an inexpensive prototype. Consequently, the air distributor was not used, and the warm air was conducted directly from the heater to the cabinet. According to the results, which were discussed in previous sections, the algae in the top shelves did not have the same amount of moisture content as the bottom shelves since the warm air was not distributed equally all over the cabinet. Thus, the air distributor plays an essential role in having a homogeneous quality of algae during the drying process.
- In order to reduce the heat loss from the heater, it can be insulated. It was witnessed that the body of the heater was very hot during the tests.
- By performing a 49-hours test, we concluded that algae lost more than 50% of their moisture content just 6 hours after the beginning of the test. Therefore, it might be helpful to set a timer for the dryer according to the drying plan.
- Based on the availability and the price of material in different places, stainless steel plates can be replaced by wooden plates. In this project, wooden plates were used since they are cheaper and more accessible for us in the University of Iceland. As long as wood does not deform, due to the high content of moisture in the air inside the cabinet, we can benefit from the advantages of wood over stainless steel.

## 7.5 Chapter summary

In this chapter, the prototype was tested, and the results extracted from a 49-hour test were presented through various graphs. Then, the moisture content of algae over time was analyzed. In the end, the design was discussed and evaluated. In the next chapter, the final design will be presented.

# 8 Final design

In this chapter, the final design based on the results of the test and design evaluation is presented. Despite some changes, the final design keeps the main concepts of the preliminary design. Figures 8.1 and 8.2 show a 3D model of the final design.

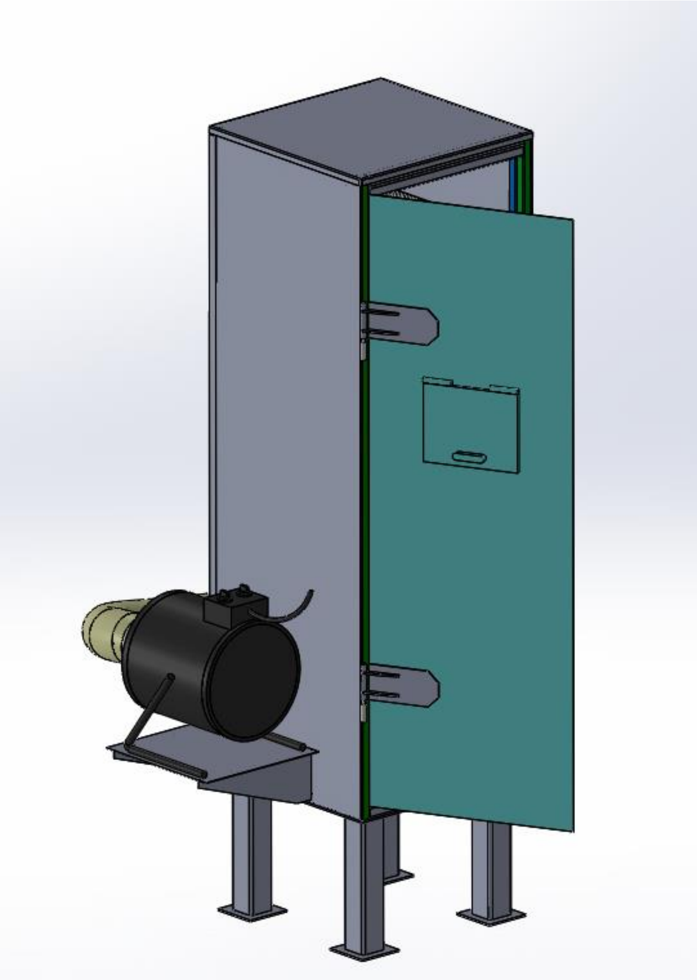


*Figure 8.1- Final design of biomass drying cabinet (front view)*

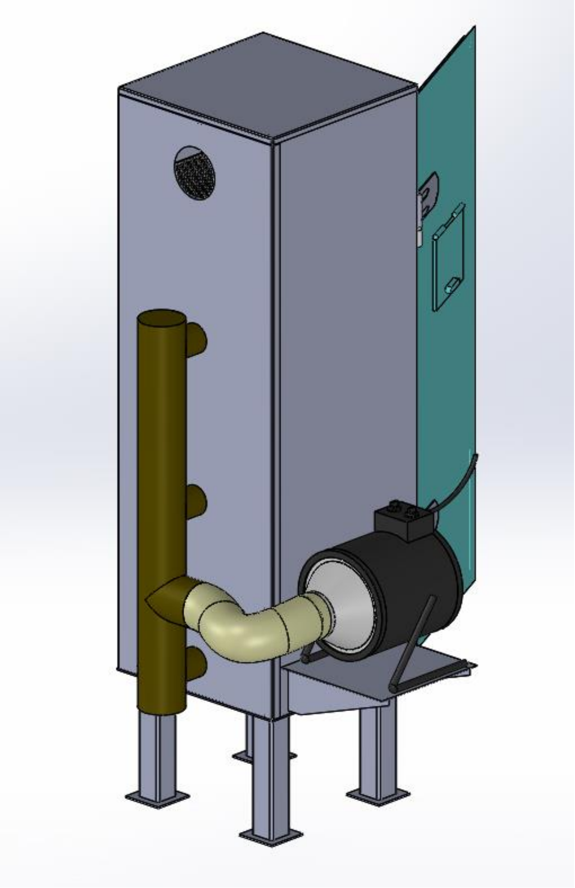


*Figure 8.2-Final design of the biomass drying cabinet (back view)*

The final design is the result of calculations, drying experiments, computer modeling, prototype tests, and design evaluation. Some of the main features of the final design are listed below.

- The final design does not reuse outlet air.
- A small hole is designed on the door of the cabinet to take out the sample during the drying process without interfering with the process.
- Air distributor, as an essential part, injects warm air to the cabinet in three different places to make the conditions identical for all shelves inside the cabinet.
- The outlet duct is located on the backplate to make the cabinet less tall.
- Electric heater provides high-temperature air for the drying process.

## 8.1 Chapter summary

In this chapter, the final design of the project was presented. In the next chapter, the whole project will briefly be discussed and some of the main conclusions will be noted.

# 9 Discussion and conclusions

In this chapter, we summarize the whole thesis and indicate some of the main outcomes of the project.

In order to run the gasifier machine, pellets can be used as fuel. For the purpose of making pellets from algae, the moisture content of algae should be reduced to a certain level (less than 20%). In this study, we briefly introduced the gasification process and reviewed different drying methods as well as various mechanisms. In chapter five, a preliminary design for the biomass drying cabinet was presented. A prototype of the drying cabinet was constructed, tested, evaluated, and revised. Then, several drying tests were accomplished by the revised prototype. Some of the major results are highlighted here.

- Based on the high cost of services and equipment as well as convenient access to cheap energy in Iceland, installation of heat recovery system for a dryer with limited working hours is not economical.
  Due to some reasons, the heat recovery system was not used in the final design. First, the dehumidifier that was used in the preliminary design was not efficient enough. Consequently, we needed to buy a more powerful condenser, which its price exceeded our budget. Second, electricity in Iceland is not expensive, and using fresh air for the drying purpose is not costly. Third, the ambient air here in Reykjavik is not extremely humid and can be used for the purpose of drying. Lastly, this dryer has limited working hours and is not designed to work continuously. In other words, this drier is not consuming electricity twenty-four-seven. Therefore, not using a heat recovery system in the final design was an economical decision.
- Maximum drying rate in the dryer happens in the first 2 hours and reduces over time. More than 50% of the mass in algae is evaporated in the first 6 hours, and the drying goal is achieved after 22 hours from the beginning of the test. As it was mentioned before, the goal of the project was reducing the moisture content of algae to less than 20%. According to the results, we reached the 20% within 20 hours of drying. Thus, the hypothesis that we can use atmospheric air heated to the relatively low temperature of ~ 50 C, a temperature compatible with a low cost geothermal or waste heat source, within an economically feasible time is proven correct by this work.

# 10 Future research

The designed biomass drying cabinet can solve the humid biomass problem. However, some details need to be improved in future studies. As an illustration, a heat recovery system can be designed for this dryer to make the design more economical since energy is costly in other countries. In addition, other sources of heat based on weather and energy cost can be applied to make the design more practical in various places. Some of the other suggestions are listed here.

- In this study, we did not focus on the heat recovery system. Many countries all over the world intend to use the biomass drying cabinet while they do not have access to inexpensive sources of energy. Consequently, it is recommended to do broader research for the purpose of reusing the wasted heat in the dryer.
- The particle size of shredded material (algae), as a major parameter in the drying process can be investigated in future works. Shredding the material before drying is an important process that makes the drying process more efficient.
- Other mechanisms for drying such as rotary drum dryers can be investigated in order to analyze the drying process with different tactics.
- Indirect drying can also be addressed as a broad subject for future studies.
- Other drying mediums such as superheated steam can be investigated for the drying purpose.
- Geothermal water, sunlight, biomass burner, etc. can be considered and studied as possible sources of heat in the drying process.

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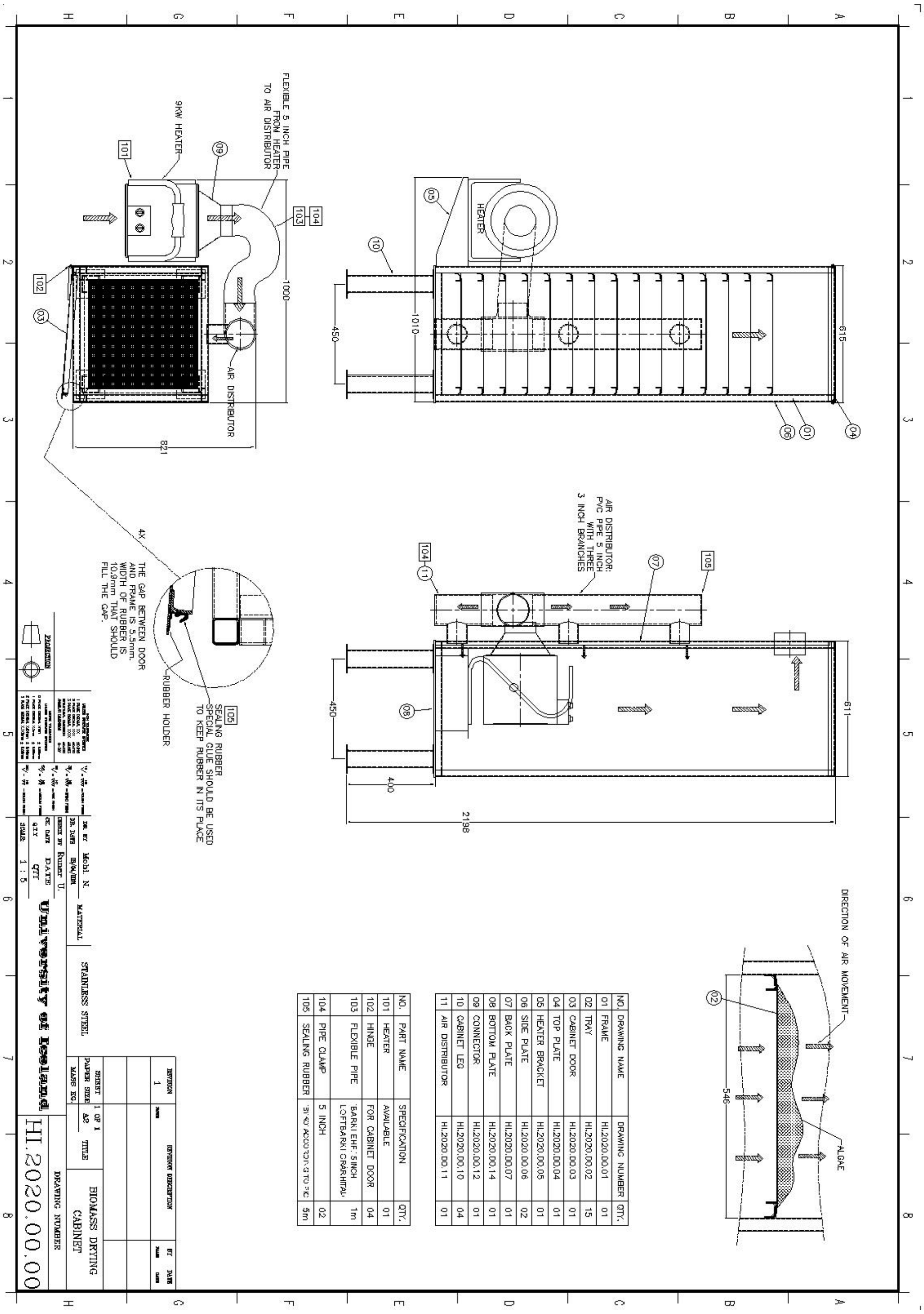
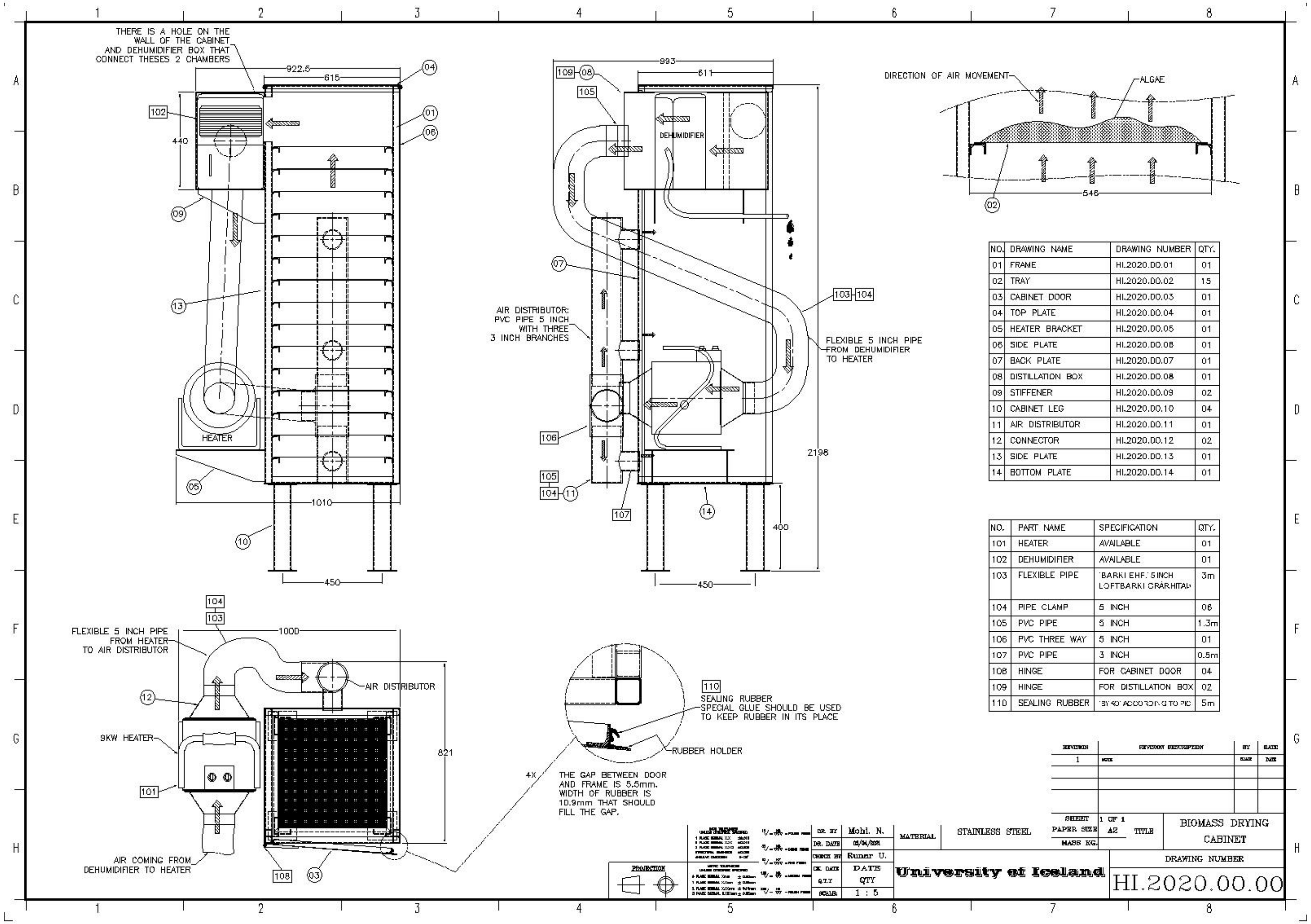
# Appendix A

## Final design



# Preliminary design



| NO. | DRAWING NAME | DRAWING NUMBER | QTY. |
|---|---|---|---|
| 01 | FRAME | HI.2020.D0.01 | 01 |
| 02 | TRAY | HI.2020.D0.02 | 15 |
| 03 | CABINET DOOR | HI.2020.D0.03 | 01 |
| 04 | TOP PLATE | HI.2020.D0.04 | 01 |
| 05 | HEATER BRACKET | HI.2020.D0.05 | 01 |
| 06 | SIDE PLATE | HI.2020.D0.06 | 01 |
| 07 | BACK PLATE | HI.2020.D0.07 | 01 |
| 08 | DISTILLATION BOX | HI.2020.D0.08 | 01 |
| 09 | STIFFENER | HI.2020.D0.09 | 02 |
| 10 | CABINET LEG | HI.2020.D0.10 | 04 |
| 11 | AIR DISTRIBUTOR | HI.2020.D0.11 | 01 |
| 12 | CONNECTOR | HI.2020.D0.12 | 02 |
| 13 | SIDE PLATE | HI.2020.D0.13 | 01 |
| 14 | BOTTOM PLATE | HI.2020.D0.14 | 01 |

| NO. | PART NAME | SPECIFICATION | QTY. |
|---|---|---|---|
| 101 | HEATER | AVAILABLE | 01 |
| 102 | DEHUMIDIFIER | AVAILABLE | 01 |
| 103 | FLEXIBLE PIPE | BARKI EHF. 5INCH LOFTBARKI CRÁRHITAÞ | 3m |
| 104 | PIPE CLAMP | 5 INCH | 06 |
| 105 | PVC PIPE | 5 INCH | 1.3m |
| 106 | PVC THREE WAY | 5 INCH | 01 |
| 107 | PVC PIPE | 3 INCH | 0.5m |
| 108 | HINGE | FOR CABINET DOOR | 04 |
| 109 | HINGE | FOR DISTILLATION BOX | 02 |
| 110 | SEALING RUBBER | BY KO ACCORDING TO PIC | 5m |