Process design for utilizing spent grain as a potential energy source for craft breweries

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Preface

This master thesis project was a collaboration between Lund University and Good Guys Brew AB. Most of the work was performed at the University at the department of chemical engineering.

Primarily i would like to thank my examine professor Mats Galbe and my supervisor Ola Wallberg at the department or chemical engineering under the faculty of engineering at Lund University for the help and guidance throughout the project.

I would also like to thank my supervisor at Good Guys Brew AB, Daniel Haag Wicksell from whom i learned a lot, who made sure that the work proceeded in the right direction and whose positive attitude was greatly encouraging.

Abstract

Craft breweries in Sweden are steadily increasing and they face a major challenge with the by-product that is generated in the brewing process. The by-product is called wet spent grain (WSG) and the biggest challenge lays in its' high moisture content which will make it spoil within a few days. Craft breweries are being conscious of sustainable practices when producing beer and the aim of this thesis is hence to design a viable process to better utilize the WSG or turn it into a useful product.

The research problem of this study is to explore ways to utilize the wet spent grain in a sustainable manner.

The research has been conducted through a literature study, focused on gaining relevant knowledge on the chemical composition of WSG. Based on the acquired knowledge a suitable solution was explored and further research within this field was conducted.

Based on the conducted research, this study confirms one major finding. Wet spent grain (WSG) can be used as a potential energy source for craft breweries. The study, however, concludes that the researched solution for this specific brewery is not financially viable from an investment point of view at this time.

Introduction

Craft breweries in Sweden are steadily increasing (The brewers of Europe, 2018). These craft breweries face challenges with energy and water supply as well as with the packaging and distribution process. Craft breweries currently face a major challenge with the by-product that is generated in the brewing process. As of today, craft breweries use the residue as feedstock for their own livestock or donates the majority to local farmers (Mussatto, S.I, 2014). Their other option is simply to throw it away in the form of landfill (Kerby, Clare, 2017), a decidedly ecologically unfriendly and potentially costly option. Other feedstock providers to local farmers are beginning to view craft brewery residue as competition and are beginning to ask for regulation of this source (Heather Vandenengel, 2014). Such regulations will inevitably increase the cost of disposal. As of today, craft breweries annually pay up to 16.000€ for their waste to be removed (Stier, J, 2010).

Craft breweries are being conscious of sustainable practices when producing beer and one option may be using spent grain as boiler fuel. Is it technically feasible and even reasonable to use spent grain as a fuel source?

This report also investigates the possible use of pelletizing spent grain as a means to improve the economics. On review, this option adds to boiler operating costs through the added cost to process the grain. This added cost reduces the savings and makes payout less attractive.

Background

Research problem

Craft breweries currently face a major challenge with the by-product that is generated in the brewing process. The by-product is called wet spent grain (WSG) and the challenge lays in its' high moisture content. The WSG has a 70 – 80% moisture content (Kunze, W, 2010) and in this state, the wet solid residue is heavy to haul and will be spoiled within a few days (Mussatto, S.I, 2006).

Craft breweries are being conscious of sustainable practices when producing beer, but in order to re-use or recycle WSG, the wet solid waste must usually first be dewatered. Currently, the most common ways to use and recycle WSG is to use it as either animal feedstock or in production of biogas. Less explored practices include turning the WSG into flour and using it as a component in baking or using it as a fertilizer when growing shiitake mushrooms (Valentina Stojceska 2011; Dr. Nicholas Brazee, 2015).

Hence, the research problem of this study is to explore other ways to utilize the wet spent grain in a sustainable manner.

Aim

The goal of this master thesis project is to design a viable process to better utilize the wet spent grain (WSG) and potentially turning it into a useful product.

The aim of this project is also to investigate different suitable options to re-use the WSG.

Disposition

This section describes the layout of this master thesis project. The report starts by introducing the overall research problem and the aim of the project. Followed by a chapter with the theoretical background on the subject based on a literature study.

The next chapter covers the chosen solution and all the calculations for the project. After that, results and discussion follow. The last part then presents the conclusions and further recommendations for the brewery.

Theory

Brewing process

Beer has been produced for approximately 7000 years (Hartman, Louis F, 1950) using a rather simple process that mostly has not changed throughout the years. In short, the entire process can be described as follows. A starch source, usually barley, is steeped in water which results in a sweet liquid called wort. This liquid is then used in combination with yeast in a fermentation process to produce beer which partially can be seen in figure 1 (Mussatto, S.I, 2006). To achieve the traditional beer taste, usually hops is also added for the flavor. This process results in very few numbers of by-products where the main one is called wet brewer's spent grain (WSG). WSG is the wet solid residue left in the vat after lautering, when the wort is separated.

Up until recently, beer producers have not yet recognized the potential value of the WSG and it has therefore not been used in the most efficient way (Salihu, Aliyu, 2011). Most of the current WSG is either given away as livestock feed or used as a simple fertilizer. Given the current worldwide focus on not wasting any resources in production; finding smart and efficient ways to use byproducts is of importance in today's process design. Therefore, finding suitable options to re-use the WSG is important, both from an environmental point of view as well as from an economic point of view (Buffington, Jack, 2014).

Though the composition of WSG can vary from brewery to brewery depending on what barley has been used and its original growth environment, the majority is composed of barley malt grain husks and parts of both the seed coat layers and the pericarp of the barley (M. Santos, 2002). Due to its origin, WSG is naturally rich in cellulose, fiber, lignin and protein. With these characteristics WSG shows potential for a lot of diverse products in different industries and markets (Mussatto, S.I, 2006).

Beer production generates large amounts of WSG and in order for the beer producers not to be wasteful with the resources it is of great importance to design a viable process that turns WSG into a useful product.

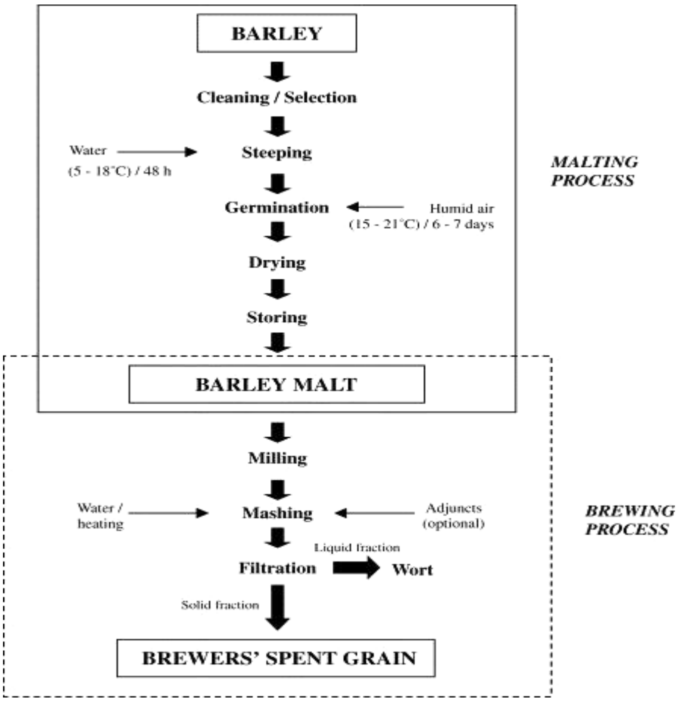

Figure 1 shows a simplified scheme of the first steps in the brewing process.

Malting

Before the brewing process can begin the grain first has to be prepared, this is done by malting which can then be broken down into three separate steps, steeping, germination and kilning. During steeping, barley grains are soaked in water (5-18 °C) for approximately 40 hours until they obtain a moisture content of 45% (Galanakis, C. M, 2018). When this level of hydration of the grain is reached the germination process begins. When the grain grows due to the water content, malt enzymes are developed, these enzymes start breaking down the cell walls and modify the barley structure. (Palmer, G. H, 1989). After about 6-7 days the malted barley is finally kilned (dried) to stop the germination, a forced air flow at 40-60 °C is used until a moisture level of 4-5% is obtained to avoid any microbial contamination during storage (Mussatto, S.I, 2006).

This step requires a lot of prior experience since every kind of grain and batch is different to another, due to this fact and the long-time requirement most craft breweries simply buy their malts directly from malt producers.

Mashing

The malted barley is then milled or crushed at the brewery to expose the most amount of carbohydrates and sugars by breaking apart the kernel (Mussatto, S.I, 2006). A representation of a barley kernel can be seen in figure 2 (Lewis and Young, 1995).

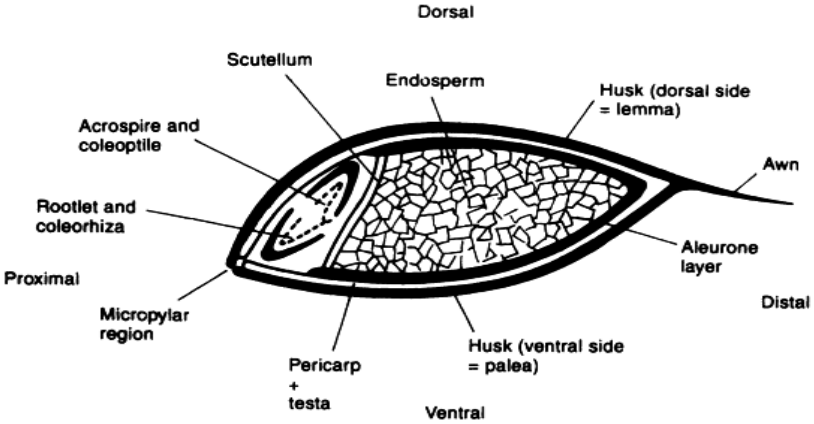

Figure 2 shows a schematic representation of a barley kernel.

The milled malt is then mixed with hot water in a tank called a mash tun which can be viewed in figure 3 below, where hops and herbs may be added for flavor. During the mash, naturally occurring enzymes from the malt are activated and starts converting the starches in the grain into simple fermentable sugars by hydrolysis, known as saccharification. The saccharification works best at temperatures of 60-70 °C and the result of this step is a sweet liquid called wort (Valentina, Stojceska, 2011).

Figure 3 depicts two mash tuns in the middle of a brewing session and one kettle to store the formed wort at Good Guys brewery in Karlstad.

Brewer’s spent grain

The sugar rich wort from the mashing is then separated from the grains by filtration and transferred from the mashing tun into a kettle for fermentation, this is called lautering. The mash that is left behind in the mashing tun is the spent grain, due to its high moisture content of >60% its formerly known as wet spent grain (WSG) and can be seen in figure 4 (Arranz, J, 2018). WSG is the major by-product from brewing beer (Galanakis, C. M, 2018), it accounts for almost 85% of the total waste from breweries (Xiros, C. S, 2012). The overall composition of the spent grain may differ dependent on variety of barley, the quality and type of other additives in the mashing step and the conditions during malting and mashing (M. Santos, 2002). The main components of spent grain are hemicellulose, cellulose, protein, lignin and lipids and the overall composition can be found in table 1.

Table 1 shows the chemical composition of spent grain (SG). All values shown are in g/100g dry material, % (w/w). N.d stands for not determined.

Component	Kanauchi et al. 2001 (86)	Santos et al. 2003 (7)	Carvalheiro et al. 2004 (87)	Silva et al. 2004 (88)	Mussatto and Roberto 2006 (8)	Celus et al. 2006 (16)	Xiros et al. 2008 (27)	Jay et al. 2008 (89)	Robertson et al. 2010 (19)	Waters et al. 2012 (9)	Meneses et al. 2013 (18)
Hemicellulose	21.8	n.d	29.6	41.9	28.4	22.5	40	n.d	22-29	22.2	19.2
Cellulose	25.4	n.d	21.9	25.3	16.8	0.3	12	31-33	n.d	26.0	21.7
Starch	n.d	n.d	n.d	-	n.d	1	2.7	10-12	2-8	-	-
Protein	24	31	24.6	n.d	15.2	26.7	14.2	15-17	20-24	22.1	24.7
Lignin	11.9	16	21.7	16.9	27.8	n.d	11.5	20-22	13-17	n.d	19.4
Lipids	10.6	3.0-6.0	n.d	-	n.d	n.d	13	6-8	n.d	-	-
Ash	2.4	4.0	1.2	4.6	4.6	3.3	3.3	n.d	n.d	1.1	4.2
Phenolics	n.d	1.7-2.0	n.d	-	n.d	n.d	2.0	1.0-1.5	0.7-0.9	-	-

Because of its very high moisture content, WSG suffers from a short shelf life and will be spoiled within a few days only (Mussatto, S.I, 2006). Due to the large amount of WSG produced year around there is a constant global demand for transportation of WSG for disposal. For every 100 L of beer produced, 20 kg of WSG is created (Mussatto, S.I, 2006). Since as much as 700g of 1kg of WSG can be water the transportation is ineffective and the short shelf life limits the transportation range to a maximum of 350km around the brewery(Galanakis, C. M, 2018) (Crawshaw, R, 2004).

Figure 4 newly lautered batch of wet spent grain from Good Guys.

Raw material analysis

During the last week of the project an analysis of Good Guys specific brewers spent grain was performed to compare results with previous literature values and look for any potential differences. The followed procedure is enclosed in appendix A and the results from the laboratory part is shown in tables 2 and 3 below.

Table 2 shows the result from an analysis of the chemical composition of Good Guys spent grain.

	Cellulose	Hemicellulose		Lignin
	Glucose	Xylose	Arabinose	
Sample, 1, % (w/w)	42.6	16.4	9.2	15.2
Sample 2, % (w/w)	43.2	16.6	9.7	14.4
Sample 3, % (w/w)	43.0	15.3	9.1	13.9
Sample 4, % (w/w)	42.5	16.4	11.1	15.0
Sample 5, % (w/w)	43.0	17.7	12.1	15.1
Sample 6, % (w/w)	43.6	14.4	9.5	14.6
Average	43.0	16.1	10.2	14.7

Table 3 shows the result from a soxhlet extraction on the spent grain.

	Maltose
Extraction 1, % (w/w)	18.9
Extraction 2, % (w/w)	20.2
Extraction 3, % (w/w)	21.0
Average	20.0

The lignin and hemicellulose results in table 2 are within the previously found values for spent grain, however the glucose content is almost twice as high as previously reported. The maltose results from the soxhlet extraction in table 3 cannot be compared to any previously known values since it is not common practice to run this analysis.

Spent grain data

Fixed carbon content

With a fixed carbon content of 41.5+-0.9% compared to 64.5+-3.0% of standard coal there is a good indicator that brewers spent grain can be suitable as a combustion fuel (Manyuchi, Mercy, 2017). The fixed carbon content can be used to estimate the calorific heat value since it is the carbon that contributes most to the heat while burning. Through carbonization by pyrolysis and creating pellets from the spent grain an even higher fixed carbon content could possibly be achieved (Celaya, A. M, 2015).

Gross heating value

The calorific heat value of brewers spent grain has been shown to be between 12.6 and 16.9 MJ/kg (Manyuchi, Mercy, 2017; Sperandio, Giulio, 2017). This is reasonable value considering its rather high carbon content and its structural resemblance to other biomass fuels with calorific heating values ranging from 15.41 to 19.52 MJ/kg (M. Erol, 2010). This confirms the possibility of using dried WSG as a fuel source.

Ash content

The ash content of brewers spent grain has been shown to be as low as 3% (Dong, N. T. K, 2003). Comparatively wood pellets and sawdust can have an ash content of around <1% (S. Caillat, 2013). A high ash content in the boiler feed has a negative impact on the boiler efficiency and lowers the calorific heat of the material, this low level of ash makes it even better for combustion.

Organic matter

Organic matter represents the part of biomass that is turned into volatile gases during high temperature combustion. A high organic matter content is directly linked to a high amount of biomass (Celaya, A. M, 2015). The organic matter of brewers spent grain is around 47.0+-0.3%. Most biomass contain a high amount of organic matter, making them more reactive than coal for example. This value can also be improved, reduced through carbonizing by pyrolysis and turning the bio char into pellets (Manyuchi, Mercy, 2017).

Moisture content

Moisture content is one of the major factors in the ability to use any biomass as a source of energy. Since the brewing process is a dominantly wet process the moisture level of brewers spent grain can exceed that of 70% (Arranz, J, 2018). Therefore, brewers spent grain must undergo some sort of drying before it can be efficiently used in combustion. The moisture level of brewers spent grain can be reduced greatly by means of drying by either mechanical pressing or drying.

Potential applications for brewers spent grain

Animal nutrition

The main use of brewers spent grain as of today is as an animal feed for cattle, mainly because of its relative rich fiber and protein content (Szponar, B, 2013). For this simple purpose it can be used either directly after wort separation, lautering, as a wet mass or after any form of drying (Öztürk, S, 2002; P.M, Townsley, 1979). The primary cattle market for brewers spent grain is dairy cattle feed seen in figure 5 (Shutterstock, SerhiyHorobets - 687319192), where it has shown to promote milk production without affecting the animal's fertility (N.G, Belibasakis, 1996). But further investigation on the possibility to use brewers spent grain for fish and poultry have been concluded (V.I, Kaur, 2004).

Figure 5 shows dairy cattle eating from a feed.

Human Nutrition

For the same reasons that it has shown good properties for animal nutrition, brewers spent grain has also been evaluated for use in cookies, bread and biscuits. Brewers spent grain for human consumption must however first be converted into flour before being incorporated in our food due to its rather large particle size after lautering (Öztürk, S, 2002; Lynch, K. M, 2016)

Successful baking results have been achieved with the incorporation of brewers spent grain in a wide range of products such as cereals, cookies, pizza, snacks and bread. Specifically, pizza dough made from a base of spent grain can be seen below in figure 6 (Spendrups, FLB Europa 2017). The results of incorporating flour from brewers spent grain is an increase in protein and fiber content but at the cost of color and flavor change. Due to these changes not all flour based products are suitable for production and in the applicable products the maximum amount that can be used is around 5-10% due to the texture and flavor (N. Prentice, 1997).

Figure 6 shows pizza dough made from spent grain in a collaboration of Spendrups and the restaurant 800 grader in Stockholm, Sverige.

Energy production

A third possible use for brewers spent grain is as a fuel source for energy production illustrated in figure 7 below (American Power & Gas, 2017). There are two major ways for energy production, either via simple combustion of the biomass to produce steam or through a fermentation process to produce bioethanol.

For the brewers spent grain to be a viable fuel for combustion its moisture content must first be reduced to <55% (Meyer-Pittroff, R, 1988). A lower moisture lever increases the efficiency of the fuel for combustion but some energy is then needed to dry the material.

For bioethanol production a hydrolysis, treatment with enzymes and acid, of the brewers spent grain must take place to convert the cellulose and hemicellulose into sugars such as glucose and xylose for fermentation. Drying and milling the brewers spent grain beforehand is necessary to achieve a good hydrolysis (Jane S. White, 2008). Milling enables higher solid leading with constant volume and improves the sugar extraction by increasing the overall surface area and allowing enzymes and the grains to have a greater contact.

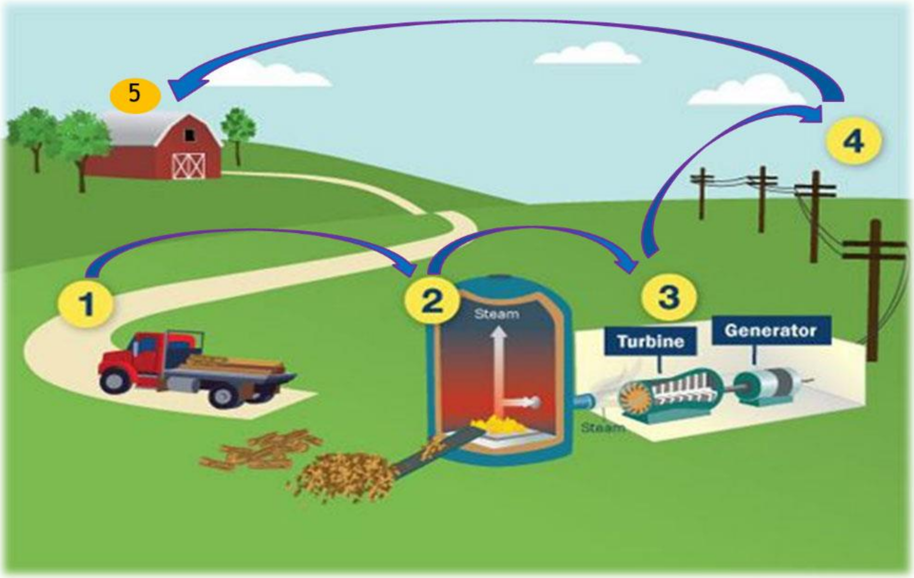

Figure 7 representation of electricity generation from a biomass steam boiler system.

Pellets

One way to use brewers spent grains as a boiler fuel is to first turn it into pellets shown in figure 8 (Sperandio, Giulio, 2017). Spent grain pellets can be pressed from a moisture content as high as 25% and therefor require less initial drying. The moisture content will decrease slightly during pressing but a final content of around 10% is desirable to make it aerobically stable for long time storage (Boessinger, M, 2005). When producing pellets, the biomass variables greatly affect the energy demand for the process and the final quality of pellets (Sperandio, Giulio, 2017).

Figure 8 display pellets and bio char made from dried WSG.

Drying

Passive

Passive drying, where the drying is done using free convection and with no added heat source can generally be executed to a achieve a dry matter of up to 85% depending on the material properties and the ambient temperatures (Roos, C, 2008). Passive drying is generally the cheapest solution, both from additional equipment cost and that it requires the least amount of external energy. A setup for passive drying with the help of sunlight can be viewed in figure 9 (Brian Williams, 2019). The few downsides to passive drying is the huge amount of occupied space needed and long the extended drying time required.

Drying time is dependent upon many parameters of both the material to be dried, shape, size and density and the storage conditions such as method of storage, air flow, temperature and humidity (Bin, Bujang, 2011).
To increase the efficiency of passive drying one should:

- Maximize natural ventilation and ensure good airflow.
- Help with airflow by attempting to raise the material off the ground on a structure that does not restrict airflow.
- Increase surface to air area as much as possible by spreading out the material.
- Position and design the drying structure to reduce any ingress of water and simultaneously allow water to drain away.

If a lower moisture content is required some active drying steps are necessary, for most modern combustion systems the result of passive drying is sufficient, however for spent grain the slow drying times with this method results in microbial growth occurring (Aivars, Aboltins, 2015).

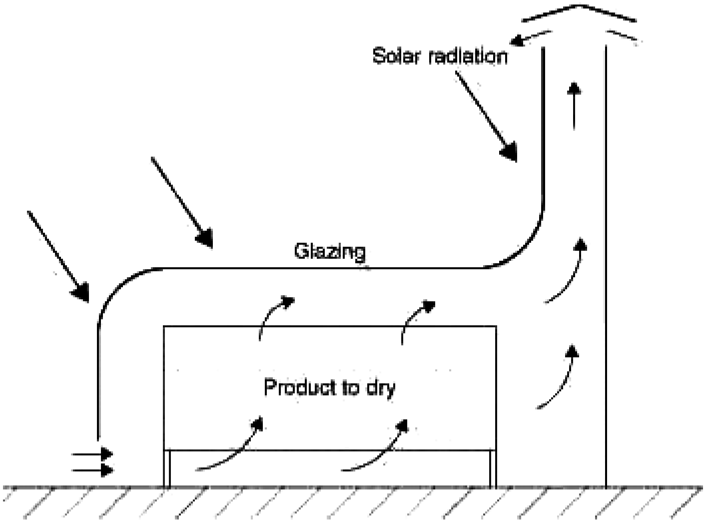

Figure 9 shows a setup for passive drying with the help of direct sunlight.

Active

If a final moisture content below of that which passive drying can achieve in the available time is required or if the drying time needs to be improved, then active drying is necessary. Active drying is when an external source of heat is added to the system to speed up the process. This use of external heat comes with an increased cost and a lower overall efficiency of the drying process compared to passive drying. Heating can be from any available source such as a dedicated heater or excess process heat. To increase the efficiency of active drying a few parameters are looked at:

- Increase the airflow artificially with the use of fans or blowers.
- Maximize the material movement, the most common way is with a rotating drum.

Mechanical pressing

The first logical step to diminish the initial moisture level of spent grain from 75-80% to a moisture level around <70% is to use mechanical force (Augusto, Copello, 2008). For this purpose, a dewatering screw press is most often used, illustrated in figure 10 (Furui Machinery). A dewatering screw press is a screw with a decreasing pitch thread and diameter. The material is feed into the beginning of the screw where the diameter is the smallest and pushed forward by the motion of the screw, friction and sometimes gravity, depending on the setup. The screw is surrounded by a mesh filter to allow any excess liquid to be removed. As the material moves forward in the press the pressure increases as the diameter of the screw increases which forces more liquid out of the material (Mahendra, Katarina, 2018). The screw is usually driven by a small electric motor and by regulating the operative variables of the screw, screw speed, the maximum possible amount of water can be removed depending on the material being pressed.

Figure 10 shows an industrial scale dewatering screw press.

Direct drying

In direct drying the material gets the required heat for drying from direct contact with the fluid, usually hot air or steam. To separate the different fluid systems, direct heating is divided into the two following categories, air- and superheated steam dryers (Wade A. Amos, 1998).

Air dryers

In air dryers, hot air acts as the medium to evaporate the water in the material to be dried while also transporting away the water vapor. In some cases, the air flow can help move the material around for a better efficiency.

Superheated steam dryers (SSDs)

The concept is the same for a superheated steam dryer, only this time superheated steam is the direct contact medium. For evaporation to occur, heat must be transferred from the steam to the drying material. The steam does however never go below its saturation temperature and therefore does not condense. The effect of the water vapor from the material is a larger steam stream at a lower temperature leaving the dryer (Wade A. Amos, 1998).

Indirect drying

In the case of indirect drying, there is a separation of the material to be dried and the heating medium in the form of a heat exchange surface. This is favorable when the drying material is sensitive, when the material might react with the heating fluid and if contamination by flue gases used for drying is not allowed.

Rotary dryers

Rotary dryers are the most commonly used drier for biomass. There are many kinds of rotary dryers, the simplest being the directly heated single-pass shown below in figure 11 (Michaud. David, 2016). In a directly heated rotary dryer the material is fed into a rotating drum where it comes in direct contact with the hot heating medium. With the rotation of the drum and help of longitudinal flights inside the drum the material is thoroughly mixed, this increases both the heat and mass transfer by ensuring the maximum surface area of the material in contact with the heating medium (Wade A. Amos, 1998).

In this dryer hot gases are directly contacted with the biomass material inside a rotating drum. This rotation is there to ensure mixing of the material and increase the heat and mass transfer by increasing the surface area in contact with the hot gases (Roos, C, 2008; Wade A. Amos, 1998).

The standard flow in a single-pass rotary drum is a co-current flow, where the high moisture biomass and hottest heating medium flow in the same direction. This setup does however not yield the best drying results. For biomass that are not concerned with high temperatures a counter-current flow can be used. In this scenario the hottest gases meet the driest materials. This results in an overall lower moisture content but with an increased fire risk (Wade A. Amos, 1998).

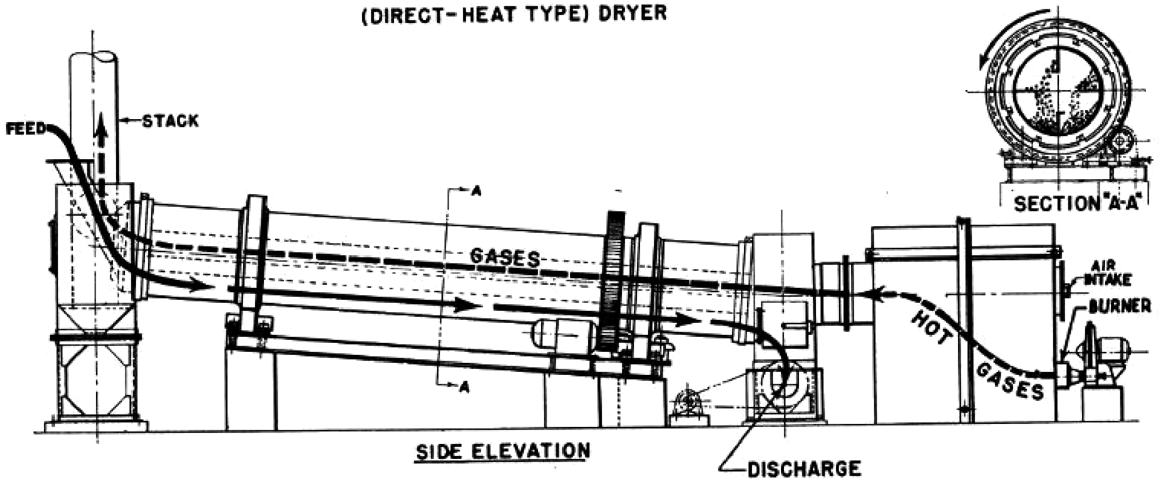

Figure 11 cross section of a direct heat single-pass rotary dryer in a counter current setup.

An indirect rotary dryer gets it heating capability through conduction, steam or hot air passes through tubes inside the drum or around a central shaft viewed in figure 12 (Michaud. David, 2016). Because of the heat exchange material between the hot gases and the biomass indirect heating are less efficient (Roos, C, 2008).

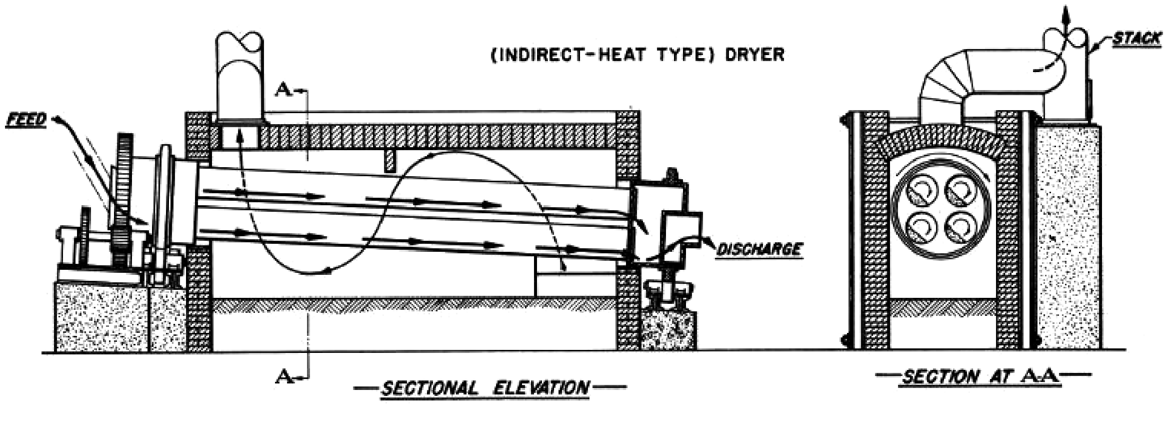

Figure 12 cross section of an indirect heat rotary dryer, also setup with a counter current flow of feed and steam.

Flash dryers

In a flash dryer the material is suspended by a hot high-velocity gas stream of air, flue gases or steam which results in short drying times. The mixture is then separated in a cyclone so that the gases may be scrubbed to remove any entrained particles, a flash dryer can be seen in figure 13 (el Hallaoui, Zhor, 2018)(Wade A. Amos, 1998). The electricity when using a flash dryer is rather high because of the constant demand of high-velocity gases to maintain the material suspended in the air, to further assist with this, the material must first often be reduced in size by a grinder. For wet materials, some of the dried material can be recycled back and mixed with the incoming wet material to improve material handling. Flash dryers have been successfully used for drying most biomass materials, including wood, sludge and bagasse (Wang, C.S, 1990).

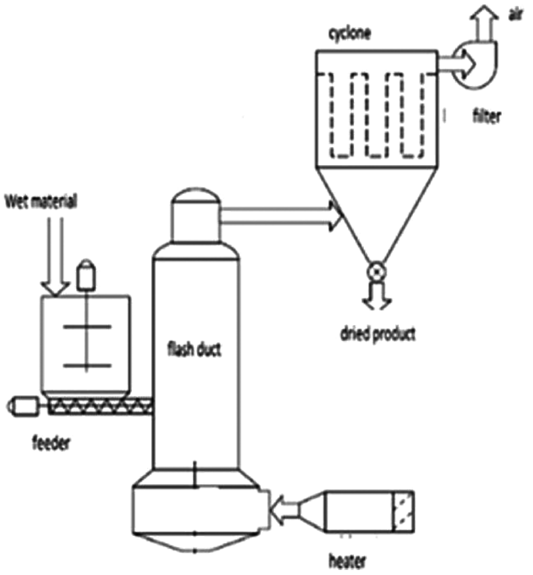

Figure 13 simple explanatory schematic of a flash dryer setup.

Benefits of drying

Even though modern boilers can handle fuels with a relative high moisture content of 50-55% it greatly reduces the efficiency of the boiler. This is because a some of heat of combustion first goes to removing all the excess water in the fuel. If dried fuel is used instead in a combustion boiler, one can notice improved results on steam production, up to 50-60% more, reduced fuel use and improved boiler operations. (Intercontinental Engineering, Ltd. 1980; Wardrop Engineering, Inc. 1990).

The main reason for all these benefits is a higher flame temperature. When dry fuel is burnt, all the heat of combustion goes into heating surrounding air. An increased flame temperature also means that the temperature gradient inside the boiler available for heat transfer is larger. This is the major reason behind the increase in steam production for the same boiler tube area. Another great benefit of the increased flame temperature is that you get a cleaner more complete combustion with a lower emission of carbon monoxide (CO).

The main benefit with using a dried fuel is the increased flame temperature in the combustion chamber. When dry fuel is combusted, all heat of combustion goes into heating only the surrounding air and any products of combustion. The increased flame temperature also increases the boilers heat transfer because of a higher temperature gradient within the boiler, more steam can be produced with the same tube area (Intercontinental Engineering, Ltd. 1980).

Biomass steam boiler

A boiler is commonly referred to as a unit that generates steam by heating up water with combustion of a fuel as the main source of heat. The steam generated can then either go directly into the process for heating or be used to generate electricity via a turbine, heat energy is transformed to work. In a boiler, the heat source and the fluid are separated by a heat-resistant material that allows for heat transfer. There are two major boiler types for biomass combustion, firetube and water tube boilers.

Fire tube boiler

In a firetube boiler, hot combustion gases flow in multiple straight pipes going through a sealed vessel filled with water, illustrated in figure 14 (IB & M). Steam is created by conduction through the pipe walls from the hot combustion gases to the water. A single burner fire tube boiler can produce saturated steam at 17 bars, this steam can then be passed through a superheater where flue gas can turn it into superheated steam if the exhaust gases are hot enough (El-PRO-CUS).

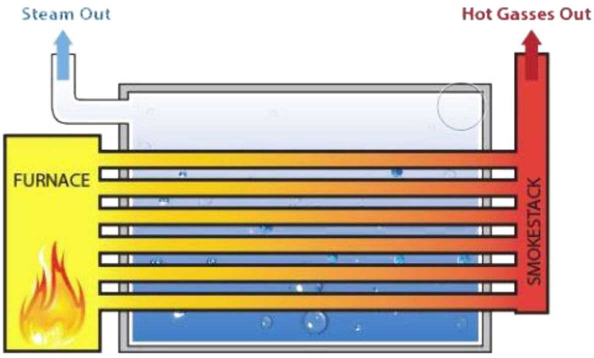

Figure 14 simplified picture of a firetube boiler.

Since the design allows easy access to the furnace, and the pipes are straight, maintenance is easy. The cost of a fire tube boiler is typically lower compared to other boilers due to its smaller and more compact design. The biggest drawback to fire tube boiler is the large amount of water to be heated, this means that the time and energy required to reach operating conditions is rather high (IB & M).

Water tube boiler

A water tube boiler is the exact opposite of a fire tube boiler. Here pipes of water go through a furnace and are heated externally by the fire as seen in figure 15 (IB & M). Water tube boilers provide greater steam output than fire tube boilers and at a higher pressure, up to 340 bar. A water tube boiler is preferred if steam consumption is fluctuating since the total volume of water is lower and the output can therefore be controlled faster (IB & M).

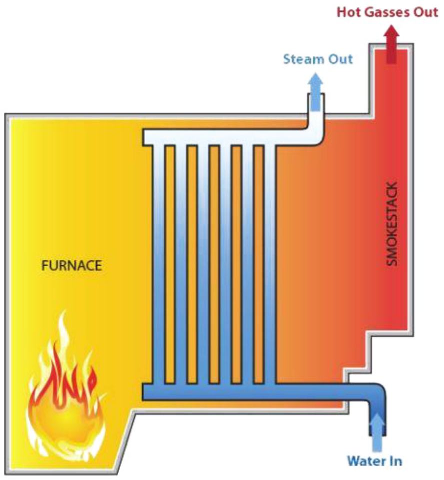

Figure 15 simplified schematic of a water tube boiler.

Design and calculations

The design aims at utilizing brewers spent grain for its energy purpose by combustion, as mentioned the material first must be dried to a relatively low moisture content to achieve a more efficient combustion. Therefore, a direct steam heated rotary dryer is chosen followed by a fire tube boiler to produce low pressure steam for the brewing process and drying.

Drying

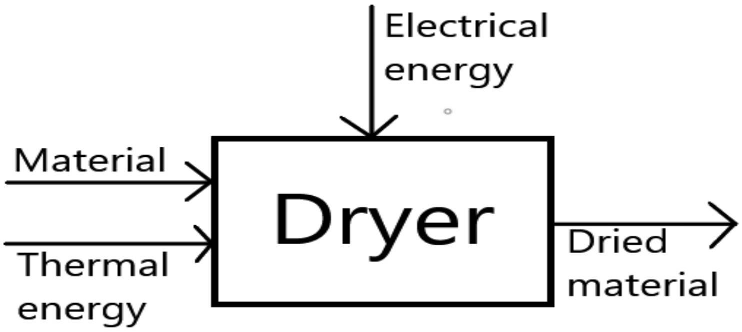

Figure 16 simplified energy and mass flow over the dryer.

Since brewers spent grain is a highly hygroscopic material the true drying calculations are dependent on the diffusion flux (ficks law) of water from pores within the material to the surface where it can be removed, due to the difficulty of these calculations a fixed value required to remove 1 kg of water is used instead. The underlying energy and mass flow over the dryer can be seen in figure 16.

The brewery produces a minimum of 4000 L and a maximum of 8000 L beer each week, this result in 800-1 600 kg of wet spent grain per week (equation 1), the weekly production always consists of 2000 L separate batches. The spent grain is dried from a moisture content of 70 to 10% meaning that 267 kg of water must be removed from the material each batch (equation 2 and 3). The final amount of DSG per batch is 133 kg. The energy requirement to remove water is set to 3100 kJ/kg (Williams-Gardner, 1971); the total energy demand for drying one batch is calculated to 827.7 MJ/batch (equation 4).

$$2000L * 2 * \frac{20\ kg}{100L} = 800\ kg \tag{1}$$

all the following calculations are done per batch of 2000 L beer.

$$400\ kg * 0.3\ (dry\ content) * 1.11\ (10\%\ moisture) = 133\ kg\ DSG \tag{2}$$

$$400\ kg - 133\ kg\ DSG = 267\ kg\ water \tag{3}$$

$$267\ kg * 3\ 100 \frac{kJ}{kg} = 827.7\ MJ/batch \tag{4}$$

Biomass boiler

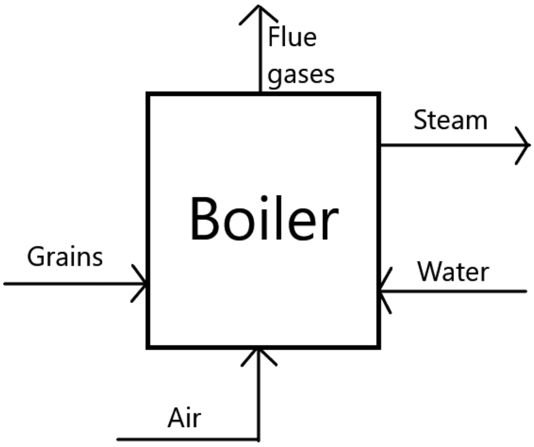

Figure 17 free body diagram of a boiler system.

Due to the Covid-19 outbreak during this study, the brewery has not been able to provide data for their steam usage, this is then calculated as follows. The boiler is designed to be able to produce enough steam to cover the loss from evaporation when boiling during mashing, which takes 1 hour. The water loss is approximated to be 400kg for a 2 m^3 vat. A free body diagram over a firebox boiler can be viewed in figure 17.

When the steam mass flow is decided, 400kg/hr, the boiler power output can be calculated with equation 5.

$$\frac{m_{flow,steam} * \Delta H_{vap}}{3600} = kW \tag{5}$$

Latent heat of evaporation is 2256.4 kJ/kg, the boiler therefore needs a power output of 251 kW.

With an efficiency of 80%, the fuel input must then contain 313.9 kW and with a high calorific heat value of 16.9 MJ/kg this means that we need to burn 66.9 kg of our dry biomass to facilitate this need.

When the brewing process is not run the boiler still needs to be maintained to keep up the temperature and pressure, the maintenance requirement is set to 10 kW and results in another 2.7 kg fuel extra that must be burnt each hour during downtime.

To cover the drying demand for one batch the boiler must be run for almost exactly 1 hour (equation 6), burning another 61.2 kg of fuel per batch. The weekly fuel demand for drying and steam is therefore 256.2 kg at low production and the weekly fuel production would be 266 kg, enough for drying, steam production and 3.7 hours of downtime.

$$\frac{934\,500\ kJ}{251\frac{kJ}{s}*3600} = 0.92\ h \tag{6}$$

Economy

The capital equipment cost is the cost of buying a direct steam rotary dryer and a firetube boiler.

A small direct heat rotary dryer with a dryer surface of 18.6 m^2 costs 162 600 \$ (2014) which is 176 000 \$ (2020) adjusted for inflation (Matche, 2014).

The cost for a fire tube boiler with the given power output is approximated to 40 000 \$ based on information found on similarly scaled wood chip boilers. 55% of the total cost for installing a boiler can be contributed to the boiler, the other 45% covers all the installation.

The installation cost for the dryer is set to be included in the installation cost of the boiler. Piping, control valves and the creating of a boiler foundation are some of the extra installation costs.

Total equipment cost: 216 000 \$ (2020)

Installation cost: 32 700 \$ (2020)

Total cost: 248 700 \$ (2020)

Operational cost is negligible since the boiler fuel is a by product from the brewery and the boiler steam production also covers the heat required for drying. A small increased utility bill for the electrical power in the rotary dryer and for the boiler water is to be expected.

Maintenance cost for these equipment's should not affect the current maintenance cost for the brewery due to the relatively small units and their modern aspect, especially since equipment knowledge already exists within the breweries staff.

An annual cost of 32 154 \$ (2020) is calculated with the equations below (equation 7,8), a depreciation of 10 years and interest rate of 5% is used. If the brewery operates at low capacity throughout the investment, 208 000 L per year, the beer price would have to increase by 0.15 \$/L (2020) to cover the investment.

$$p = \frac{(\frac{i}{100})}{1-(1+\frac{i}{100})\text{^}n} \tag{7}$$

p = annuity
n = depreciation time
i = interest rate

$$Capital\ Cost * p = yearly\ cost \tag{8}$$

Discussion

The largest challenge with this project is the relatively small-scale production of spent grain with a current maximum of 1 600kg wet mass per week at peak production. Before Covid-19 hit the brewery had an expansion plan of 50% in the future – this would greatly benefit the economic gain from this solution.

With the current revenue (approx. 300 000 $ (2020)) and profit for the brewery the possibility to do this investment organically by sales is low. However, if outside investment can be found the designed solution is financially stable.

Due to the nature of brewing on this scale, the mode of operation is batch production. This means that the drying and boiler will not have a constant feed, this mostly affects the boilers efficiency since not enough fuel is created to maintain it during downtime and it will have to be cold started over and over again.

To keep the equipment capital cost as low as possible, no equipment to enrich or create any pellets is included. If investment possibilities opens up, this would be recommended since the calorific heat value then can be increased at a low extra cost besides equipment.

A fire tube boiler is chosen for its lower capital cost and possibility to deliver low pressure steam, for a larger brewery a water tube boiler might be considered to also be able to generate electricity from the steam.

The presence of maltose and the following high amount of glucose from my own analysis suggests that maybe Good Guys brewing process is not perfect. Some of the maltose in the grain is not utilized properly during mashing and the result of this is a wort containing less than maximum fermentable sugars.

Conclusion

The spent grain produced by the brewery can be utilized in a better way, both from an environmental but also economic point of view. The biomass can be used as either a cheap source of energy via combustion or for adding extra nutrition to food products.

The suggested process design matches the breweries steam requirements. Even though the capital cost investment is rather high for a craft brewery this size the solution can help with the company's economy, both by reducing the demand for external steam for heating but also removing any cost related to the disposal of the spent grain.

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Appendix

Appendix A: NREL – Determination of Structural Carbohydrates and Lignin in Biomass, Laboratory Analytical Procedure (LAP). https://www.nrel.gov/docs/gen/fy13/42618.pdf