Engineering of Beer: Hard Work or Too Much Fun?

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Abstract – It is human nature to give very little attention to available staple foods and drinks and their industrial production. That, unfortunately, is especially true for malt beverages. Beer, an example of such, is one of the oldest known and widely consumed by man. During the brewing process grains are converted through fermentation to produce desirable and distinct sensory characteristics. Since as early as 500 BCE, beer making involved many scientific disciplines including agriculture, chemistry, biology, pharmacology. Initially, scientific contributions were at the empirical level but at the end of the 19th century beer production became the subject of analytical research. As customer demand rose and subsequently mass production increased, the brewing industry applied a whole spectrum of new technical, biochemical, microbiological, and genetic inventions boosting the involvement of the scientific world. It has been said 'Brewing is one of these things that can keep a curious mind very interested and very active.' Then, why not bring it to the engineering classroom and make our students the envy of their peers? A modern brewing engineering education would expose students to principles of fermentation sciences, systems design and many areas of engineering, and would also involve discussion of social, cultural, and ethical implications of food and beverage production. The brewing process is energy intensive and uses large volumes of water. It also produces vast amounts of waste, both liquid (wastewater) and solid (spent grains, hops, yeast). Spent grains are generally used as compost and livestock feed but could also serve as petroleum alternative or be burned and turned into heat or electricity to power machinery. This article outlines the steps used in beer brewing process and discusses various topics that could be easily integrated into an engineering curriculum.

Keywords: brewing, industry, environmental sustainability, waste

HISTORY OF AMERICAN BREWING INDUSTRY

Beer is defined as a fermented alcoholic beverage made of malted cereals, water, hops, and yeast. The cereals used in beer production do not contain sufficient quantities of fermentable sugars in the harvested state and must first undergo modification during the malting and mashing steps to yield carbohydrates that yeast can convert during the fermentation step into ethyl alcohol and carbon dioxide. Many countries allow additional substances to be used. For instance, expensive barley malt is often supplemented with less expensive unmalted cereals such as corn, rice, or wheat. In addition to reducing costs, the use of unmalted cereals contributes palatable flavors to the beer. Hops are the dried flowers from the female hop (Humulus lupulus) plant and contribute flavor and antibacterial compounds to beer. Yeasts are the predominant fermentation organisms used to make beer worldwide [1].

Evidence shows that brewing of beer was a popular practice in Mesopotamia before 3500 BCE and started involving other disciplines like agriculture, chemistry, biology, and pharmacology around 500 BCE. Beer offered people a

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flavorful alternative to drinking water which was often not only unpalatable but also contained potential dangerous pathogenic organisms. The boiling and fermentation processes involved in brewing removes waterborne pathogens [1]. Beer was also thought to posses therapeutic properties. Recipes for turning barley bread into a beverage have been found in ancient Sumerian and Egyptian ruins. In addition to being a foodstuff, beer played a central role in religious belief and ritual practice. It was a well-loved drink of the Scythians, the Celts, and the Germanic tribes, where it was brewed as daily household food by the women. Baking and brewing were women's work in all early cultures [2]. Some scholars think certain American Indian tribes made their own beer long before the European settlers brought their favorite beverage over the seas [3].

Beer has been a part of America's history since its earliest days. Colonists in the New World arrived and were brewing beer by 1587 [4,5]. The first commercial North American brewery opened in 1632 in what was then New Amsterdam (current-day Manhattan). There were about 130 breweries in 1810 and their total product was a little less than 200,000 barrels per year [6]. By the 1870s, there were more than 3,200 breweries in the United States [3]. Then came Prohibition (1920-1933). Beer was once again legalized in 1933, but a year later, just over 700 breweries were in existence. As industrialization and consolidation increased in the decades that followed, the number of breweries kept dropping. By 1983, only 80 breweries remained in the U.S. But just under the noses of the big brewing concerns, a revolution was underway.

After Congress legalized home brewing in 1978, interest in non-traditional beers began to grow. By the mid-1990s, the microbrew and brewpub craze had exploded. The number of breweries more than doubled in one year, between 1995 and 1996, to over 1,100. The trend tapered off a bit after that, but the craft beer market has continued to expand. As of August 2012, there were 2,126 breweries (including brewpubs) in the U.S., with another 1,252 breweries in the planning stage; 97 percent of these businesses are craft brewers.

While beer is consumed worldwide, on a per capita basis the leading beer consuming countries are the Czech Republic, Ireland, Germany, Austria, and the United Kingdom. While US per capita beer consumption in 2002 was about half of that consumed by the leading European countries, it was greater than the volume of milk and bottled water consumed in the country [1]. As a region, the Southeast has the second-highest per capita beer consumption, behind the Midwest. In Tennessee in 2010, the average per capita consumption of liquor and wine was 1.24 gallons and 1.3 gallons, respectively, compared to 19 gallons of beer.

The beer production procedure consists of four stages: malting (based on germination of barley); wort production (also called mashing, i.e. extraction and hydrolysis of the components of malt and possibly other cereals, which creates the wort or 'extract' – a solution of carbohydrates for the most part, followed by separation of non-soluble components and boiling with hops or hop extracts); fermentation (in most cases divided into primary or main fermentation and lagering or secondary fermentation); and down-stream processing (filtration, stabilization, bottling, etc.) [7]. Figure 1 illustrates the process of beer production.

ENGINEERING OF BREWING

The brewing of malt beverages was initiated as a kitchen "art and mystery" which developed into a trade. The early brewers were often practical men who used "rule-of-thumb" and knew little about barley growth, malting, and fermentation. Flavor was not the concern of these tradesman but rather alcoholic strength which was essential to ensuring stability and pathogen removal. The first ales were probably flat, muddy, sour, and highly intoxicating. A modern brewer is usually well grounded in science. The modern brewer must be a mechanic to know all about the structure of a complicated modern plant, the working of pumps, boilers, engines, ice machines, etc. He or she must be an engineer and understand all about combustion, fuel consumption, cold production, efficient drainage, and proper ventilation. Finally, he or she must have an adequate knowledge of chemistry and biology to achieve and repeat good qualities of beer [6].

A number of developments around 1880, such as the ability to artificially manufacture ice and the expansion of the nation's infrastructure (railroads), would eventually transform distribution and centralize production of beer and in the process alter the local nature of the industry. Pasteur's seminal study on the fermentation process and the use of pasteurization was published in 1876. The crown cap bottle closure, an invention which greatly improved the durability of beer, was developed in 1892 [8]. At the beginning of the twentieth century, field experiments

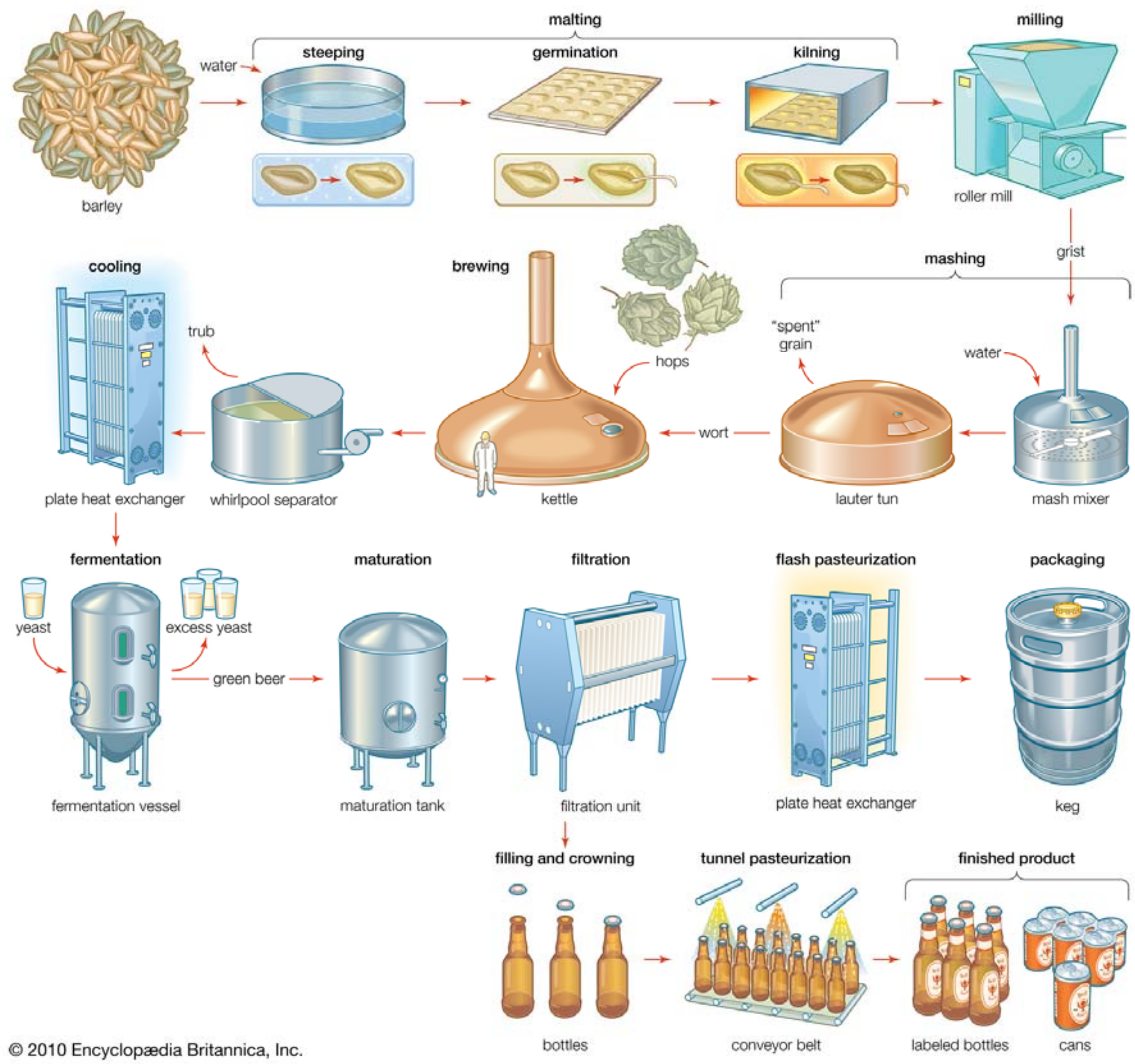

Figure 1. Beer production process flow [9].

were conducted on the influence of soil, season, and manures on the yield and quality of barley grown for malting; new varieties of hops that were more prolific and able to resist disease were developed; important work was being done on the properties of the yeast used for fermentation; and the effect of hydrogen-ion concentration on the character and stability of beers was studied [10]. The combined work of representative from all branches of the brewing industry, botanists, chemists, bio-chemists, and growers of barley and hops increased the value of beer and the brewing trade [11]. The field of pharmacology may also profit from these advancements as barley and yeast are the raw materials from which valuable medicaments such as malt extract and nucleic acid are derived [12]. Today the malting and brewing industry applies a whole spectrum of novel technical, biochemical, microbiological and genetic inventions [7].

An example beer production mass balance showing water and energy inputs and outputs with respect to residues and sub-products, liquid effluents and air emissions is depicted in Figure 2. The brewing process is energy intensive, especially in the brewhouse, where mashing and wort boiling are the main heat generating processes with high fuel consumption. Energy consumption in the brewing process is associated with heating, cooling, mechanical operations, and direct non-process uses such as facility lighting and heating /cooling. The typical cost of energy and utilities amount to between 3% and 8% of a brewery's general budget [13], depending on brewery size and other variables. Brewery processes are relatively intensive users of both electrical and thermal energy. The carbon footprint of a brewery can be optimized by adopting spent grains combustion and the use of solar or geo- thermal energy. In addition, the equipment could be arranged so that everything flows by gravity, thus avoiding unnecessary pumping.

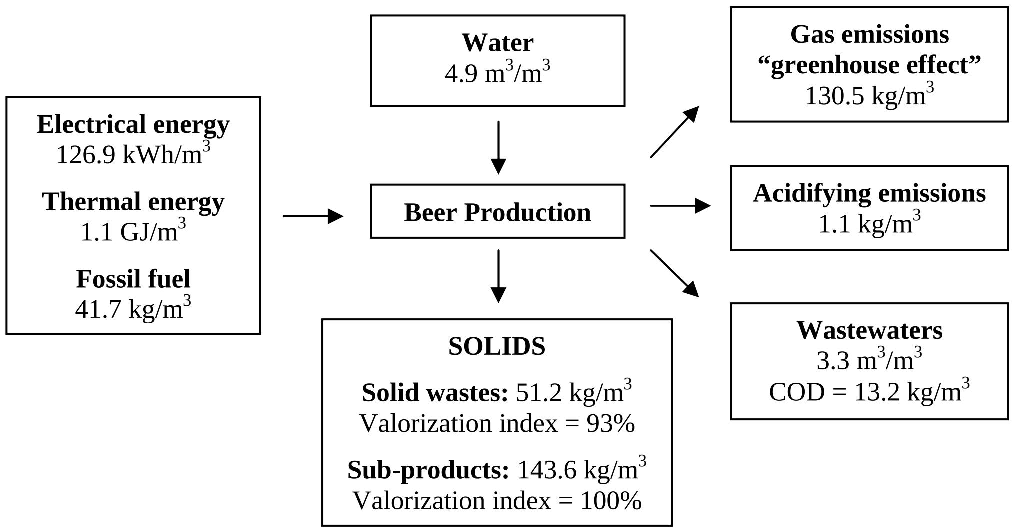

Figure 2. Mass balance applied to Unicer SA breweries representing specific values, i.e., values per m^3 of produced beer [13].

Redesign of the brewing process to maximize recovery of by-products and reuse of effluents is considered the most plausible approach to improving eco-efficiency. Achieving efficient and cleaner production will require brewers to go green by adopting new brewing technologies with efficient energy consumption, reduced odor emission, efficient water consumption for cleaning and cooling purposes, prevention of losses, and reuse of treated wastewater.

Brewing industry needs to focus on recycling all materials and by-products that are generated throughout the brewing processes. Where possible, breweries can also resell these materials and by-products, which eliminate the need for disposal, as well as providing a source of revenue. Waste and by-product management can also be driven by the secondary market value of by-products. The secondary uses of brewery waste and by-products include:

i. Malt husks and spent grain - Animal feed component
ii. Wet and dry yeast - Animal feed component or food flavoring for human consumption
iii. Labels and paper - Cardboard and paper manufacturing
iv. Glass bottles - Glass manufacturing
v. Metals - Various metal products, including aluminum cans
vi. Wastewater sludge - Soil improvement and organic fertilizers

Brewer's spent grains are generally used for the production of low value composts, livestock feed, or disposed of in landfill as waste. Surplus yeast is very high in protein and B vitamins, and may be given to the animal feed industry as a feed supplement. Brewer's grains provide protein, fiber, and energy which makes them desirable in a variety of diets. The incorporation of spent grains into fish-feed (carp) was investigated in India. The effects of beer factory sludge on soil properties and sugar beet growth were investigated in Turkey [14]. In the U.S., brewers grains and other brewer's by-products are fed to pigs, sheep, horses, dairy and beef cattle, and poultry. The chief concern about the use of wet brewer's grains relates to spoilage. An uncovered pile of wet brewer's grains usually have a storage life of less than 5 to 7 days [15]. If not used quickly, wet brewer's grains spoil resulting in a less palatable product that may cause health concerns.

During fermentation yeast cell mass increases three- to six-fold and when it is finished most of the yeast is collected as surplus yeast. Beside pure yeast the solids collected, called trub, contain particles of the malts and hops used [16]. Unprocessed trub can be used as animal feed. Yeast absorbs nutrients and flavors from the wort. Once it has been separated, inactivated and debittered it can be sold as 'brewer's yeast,' a popular dietary supplement with a high nucleic acid count which is an important component of cell development. Other vitamins and minerals contained include folic acid, vitamin B12, potassium, thiamin, niacin, and chromium. Brewer's yeast is also low in calories, fat, sodium and carbohydrates, which makes it great for people with dietary restrictions [17].

INTRODUCING BREWING TO ENGINEERING EDUCATION

This ancient craft can and should be introduced to university students not only because it provides many engineering topics for research and investigation but also for the reason that it is often regarded as a hot and interesting topic among the students [18]. The brewing industry's needs and problems related to the processes, resources used, and wastes created can be solved at universities often at little cost while providing an excellent hands-on learning experience to the students. Engineering projects in the real world require the combination of innovation and diverse disciplines. Brewing studies provide an opportunity to seek assistance from non-engineering students and faculty. Brewing can serve as a source of engineering design across the curriculum. The following list provides examples of brewing industry's topics and university specializations that could be involved. These are prime areas for interjecting real industry problems into engineering courses.

1) Acceleration of brewing process

Engineering specializations: chemical, environmental, industrial, mechanical;
with help from chemistry and biology students

Chemical engineers coming fresh into the brewing industry are astonished to encounter malting and fermentation processes each lasting a week or more [19]. They are convinced that there must be a better way. Shortening of the conventional brewing process has been one of the most favored alternatives for improving economics and increasing the capacity of a brewery with minimal money investment. The process can be shortened by either accelerating the fermentation and lagering or by producing beer in a continuous process [20]. Unfortunately, the higher process temperatures, large amounts of yeast and stirring or aeration during fermentation used to accelerate the process will stimulate the formation of strong off-flavors. Studies show that the total brewing process can be shortened from the conventional 5 weeks to 2 weeks when recombinant yeast strains are used. However, every time the brewer modifies malting, mashing, or fermentation conditions, the flavor and aroma of the final product may be adversely affected. These aesthetic considerations are why brewing depends on biochemistry and will continue to provide chemical engineers and biochemists with challenging and satisfying problems for the forseeable future [21].

Yeasts immobilized on gluten pellets increase the rate of fermentation and can be used to produce beer of satisfactory quality. This faster fermentation rate allows fermentation at 0°C to have about the same productivity as an industrial batch processes operating at 12-15°C. In addition, the low temperature fermentation results in a product with improved aroma and taste [22]. Mathematical models for dynamic optimization of three control variables: temperature, top pressure and initial yeast concentration are available allowing the reduction of the fermentation time by 33% while preserving the final aroma [23].

2) Reduction of alcohol content

Engineering specializations: chemical, environmental;
with help from chemistry and biology students

The reduction of ethanol in alcoholic beverages, especially beer, is of great commercial interest. Consumer demand for these lower potency beverages is continuously increasing due to both an increase in health conscious behaviors and stricter laws regarding drinking and driving. Current methods producing low-alcohol beer, i.e. manipulated fermentation or post-fermentation removal of ethanol, result either in a 'worty' taste or a loss of aroma components. In addition, the elimination of ethanol based on distillation or dialysis is expensive and labor intensive [24,25]. An alternative technique to produce beer with reduced ethanol content could be established by providing the breweries with a genetically modified yeast strain that forms less ethanol during complete fermentation of wort sugars. The future goal of metabolic engineering would be to combine the optimization of ethanol reduction and by-product formation in order to achieve a low-alcohol beer without impacting flavor and aroma.

3) Increase of alcohol content

Engineering specializations: chemical, environmental;
with help from chemistry and biology students

As could be expected, increasing the ethanol levels to create a higher potency brew is also of interest. High-gravity brewing is the process of producing and fermenting wort at substantially higher concentrations than needed for the final beer. The use of high-gravity worts in the brewhouse is advantageous as it allows a greater volume of beer to be produced without expanding existing facilities. Although the primary objective of high-gravity brewing is to increase brewing capacity, there are a number of additional advantages such as reduced operating costs, improved beer stability, smoother taste and greater flexibility. The drawbacks of this process include decreased material efficiency, as well as reduced foam (also called head), stability, and flavor matching. The effects of initial wort gravity, fermentation temperature and nutrient supplementation leading to maximized ethanol production rates have been studied [26].

4) Replacing barley

Engineering specializations: chemical, environmental, industrial, mechanical;
with help from chemistry and biology students

Why use barley, or malt barley specifically, when any source of fermentable carbohydrates could be used? While barley gives beer special color and flavor, these characteristics can be provided through post-fermentation additions [19]. It was once believed that beer could not be produced without barley. However, it has been well documented that cereals like sorghum, millet, and maize have the potential to be alternative substrates for conventional beer brewing. Opaque beers have been produced in tropical climates using these cereals. Other cereals (rice and maize) and pseudocereals (buckwheat, quinoa, and amaranth) have been investigated as brewing ingredients to meet consumer demand for beers that are gluten free and contain compounds that are perceived to have positive effects on health [2]. Currently only sorghum, millet, and buckwheat appear to be successful gluten-free beer ingredients, while others have only shown adjunct possibilities.

Further research work is necessary to develop products that meet the tastes and consumer habits of the ‘barley beer’ countries. The food potential of sorghum resides in the ability of the plant to grow well in the semi-arid regions of the world. The USA is a major producer of sorghum but the grain is not consumed as human food, while in Africa and India the grain is a major source of food [27]. In terms of starch gelatinization temperature and the properties of starch and protein, the grain of sorghum is similar to that of maize and is usually used to produce lager beers. In order to obtain optimal extract yield containing sufficient sugar/protein extracts from sorghum malt, a controlled temperature mashing regime is required [28].

5) Turning brewing waste into energy

Engineering specializations: chemical, environmental, industrial, mechanical;
with help from chemistry and biology students

Spent grain can constitute as much as 85 percent of a brewery’s total by-product [29]. The wet, spent grains produced spoil quickly and therefore must be removed rapidly from the brewery. Dry spent grain could be stored but drying is prohibitively expensive. Beside the previously mentioned use of spent grains in agriculture as composts and animal feed or as additives in human food, there are some innovative energy related approaches to managing this waste stream. The grains can be burned as an alternative fuel to fire a steam boiler that provides heat in the brewing or grain drying processes or powers a turbine for electricity generation. Another strategy is to use an agricultural anaerobic digester to break down the leftover grain into methane. This methane can be used to power brewery systems that run on natural gas including the boiler. This has the potential to create a perpetual material to energy loop that conserves energy, saves money, and reduces waste production.

Breweries can also look outside their own operations for opportunities to reduce the impact of their waste production. Coors Brewing has been producing ethanol, a petroleum alternative, with their spent grain.. In Japan, the Akita Research Institute of Food and Brewing has developed a new technology that drastically reduces the cost of producing polylactic acid, the spent grain-derived foundation for the production of biodegradable plastics [30].

6) Preserving water

Engineering specializations: chemical, environmental, industrial, mechanical

Another environmental impact of the brewing process is the large volumes of water it consumes. In addition to the water used for the production of beer itself, it is also used for cleaning and sterilizing a variety of the unit processes. A large amount of this water is discharged for treatment as wastewater [13]. It is widely estimated that for every one unit of volume of beer brewed, close to ten units of water are used in the brewing, rinsing, and cooling processes. This water must then be disposed of or safely treated for reuse, both of which are costly and/or problematic for most breweries. As a result, many brewers are searching for ways to reduce water usage during the brewing process and/or means to cost-effectively and safely treat the brewery wastewater for reuse. Reverse osmosis and similar techniques are commonly used to reduce ionic content and eliminate pesticide residuals in brewing wastewater [25].

7) Innovative equipment and processes

Engineering specializations: industrial, mechanical

As in any other industry, brewers are always seeking new, improved, energy efficient and cost effective technologies to use in their brew houses. Heat pumps can be used to raise the temperature of waste heat so that it can be re-used for the brewing processes or space heating purposes. These systems require far less energy than regular boilers [31].

In addition to increasing the quality and yield of the beer, separators for beer clarification can save valuable process time. The use of a separator for yeast removal allows the hot wort to be processed immediately, rather than having to wait for cooling of the fermentation vessel to cause the yeast to settle out. This separation method allows the beer to be cooled in-line with a plate exchanger, which is more energy efficient. A conventional process uses a whirlpool but adding a disc-stack separator or decanter centrifuge may highly reduce the beer losses [32].

The use of membranes in beer filtration and addition or removal of gases to/from beer is crucial. In addition "cleanability" of the membranes is critical to the successful application of the technology. In order to prevent the biological spoilage of the product, it is essential that the membrane be kept free of bacteria. The potential impact of new, membrane-based technologies such as crossflow (Figure 3) and hydrophobic gas membranes on the brewing process should be evaluated [25].

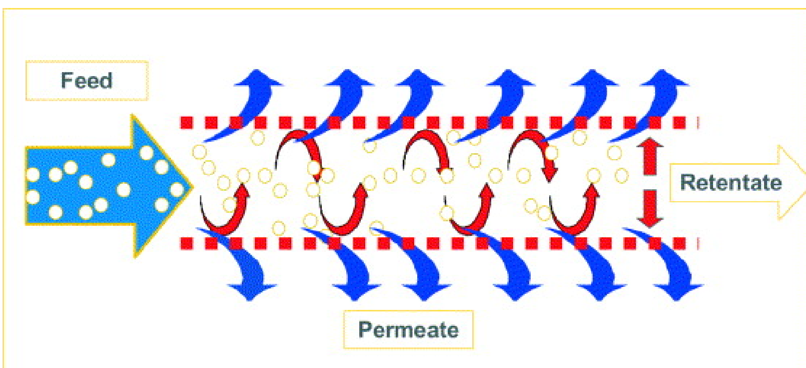

Figure 3. Schematic showing the principles of crossflow filtration [32].

Daily analyses of the brewing liquids are often performed manually by means of paper-filtration or centrifugation. New technologies that enable a continual on-line measurement of the mashes throughout the fermentation process are constantly under investigation [33].

CONCLUSIONS

Aspects of many engineering courses (fluid mechanics, heat and mass transfer, materials, process design, process control, power, machine design, statics, engineering economics, pollution control, optimization, etc.) can be brought to bear in the evaluation of the brewing process. These specialties could be used in conjunction with sustainability and green design concepts to optimize design and operation of a brewery. Moral and religious concerns with the production of alcoholic beverages could be an interesting focus of a module on ethics and societal concerns.

Food engineering (of which brewing engineering is a part) continues to be a stable and growing area of employment for engineers. It is clear from the previous listing of the major brewing industry challenges that the topic of beer brewing is a rich area for multi-disciplinary design problems. In each of the seven areas discussed, several engineering and science disciplines are required to work together. Brewing could be a fertile area for true multi-disciplinary senior design projects. Engineering a product where taste is a paramount attribute, adds to the challenge. The topics associated with brewing engineering can be translated to many other food products and the processing associated with their production.

The use of beer brewing as means of piquing student interest and motivation might be beneficial. One must also assume that some percentage of students will not find the topic interesting due to personal views or moral beliefs related to alcoholic beverages. Still the inclusion of brewing engineering or food engineering topics as design problems is a worthy undertaking to help spark student interest and possibly assist in retaining engineering students.

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