Spirited Engineering: An Introduction to Distilled Spirits Production

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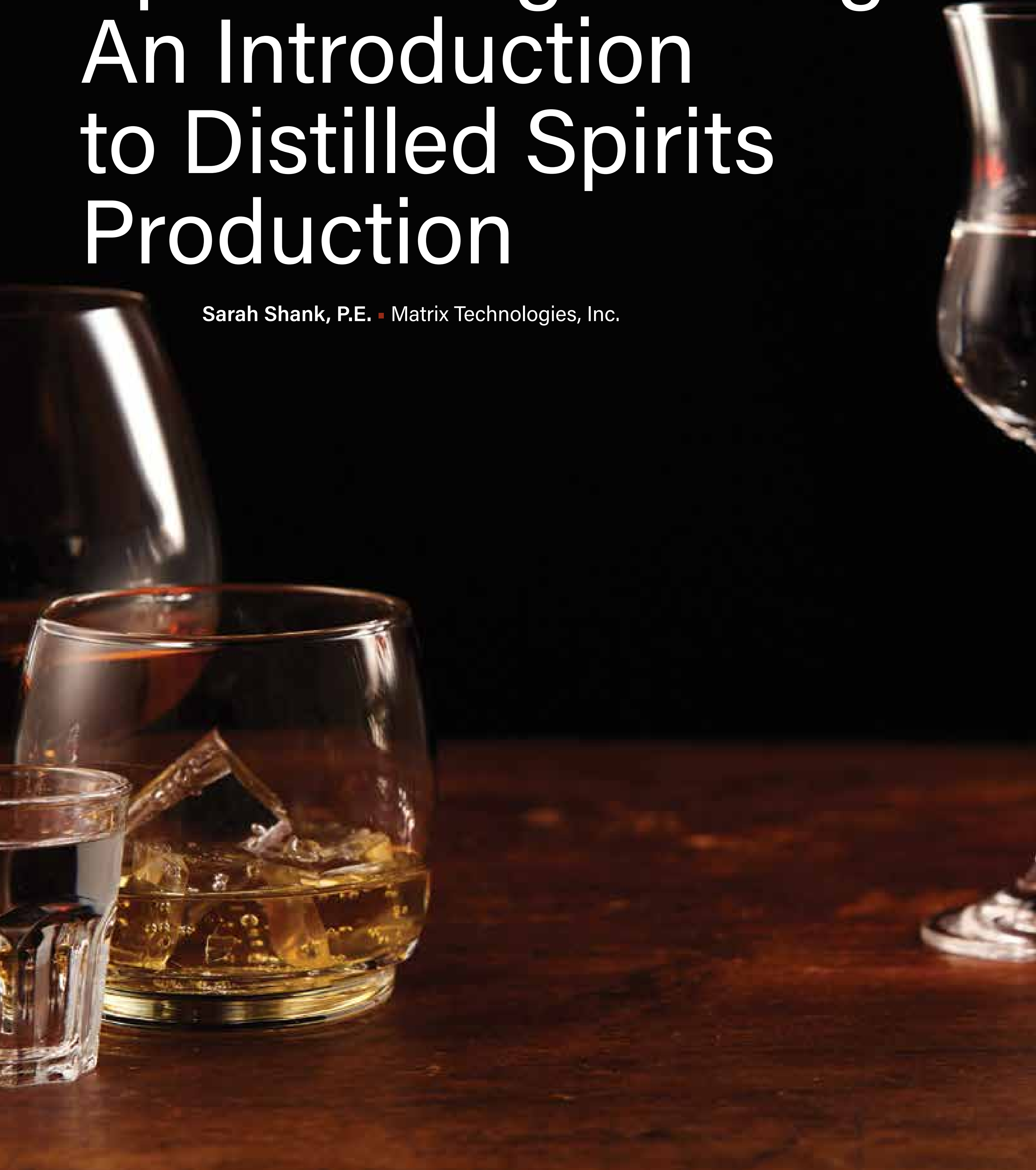


The production of distilled spirits — like vodka, tequila, and whiskey — has fascinating ties to chemical engineering.

From the perspective of a design engineer, there are many parallels between spirits production and chemical engineering. For example, spirits production facilities include several unit operations, like fermentation, distillation, heat exchangers, and reactors. The facility design includes utilities, hydraulics, and instrumentation, and requires equipment sizing and process safety considerations, providing a practical application for many parts of a chemical engineer's education.

This introduction to distilled spirits will follow the path of ethanol, beginning with the source material, processing through a distillery, and, finally, bottling to highlight the engineering behind your favorite distilled beverage. If you have ever wondered how your gin martini goes from grain to glass, this article is for you.

Introduction

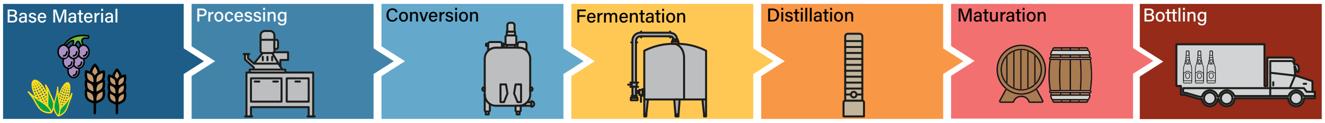
The Federal Alcohol Administration Act, which was created in 1935 to regulate the alcohol industry after prohibition, defines a distilled spirit as "ethyl alcohol, hydrated oxide of ethyl, spirits of wine, whiskey, rum, brandy, gin, and other distilled spirits, including all dilutions and mixtures thereof for nonindustrial use" *(1)*. The Alcohol and Tobacco Tax and Trade Bureau (TTB) further differentiates distilled spirits into classes and types for labeling *(2)*. Each class, type, and end product has distinct characteristics such as color, flavor profile, aroma, and aging requirements that set it apart. However, they each follow the same general manufacturing process (Figure 1).

A base material contains sugars, which are made accessible for yeast to digest and convert into alcohol. That alcohol is purified and concentrated using distillation to create a spirit. Table 1 includes six of the classes recognized by the TTB organized by the steps in Figure 1 *(2)*.

Base material

Whether the spirit recipe includes fruits, vegetables, or plants, the process begins with a base ingredient that contains sugar — either in a simple (glucose or fructose) or complex (carbohydrates) chemical structure. The base could be grown on the same property, in the same region, or completely remote from the distillery. The base could be owner-grown or provided by a third party. A base could also be an unconventional source of sugar for a distilled spirit like milk or honey.

The base ingredient and where it's grown or distilled can determine what spirit results from the rest of the process. For example, grain cannot be made into rum. Some products, like tequila, can only be produced in a specific geographical region. In Mexico, that is called a "Denomination of Origin." A spirit could be produced identically to tequila



▲ **Figure 1.** Most distilled spirits are manufactured following the same general progression.

Table 1. Each type of spirit has specific requirements for every step of production, from base material through bottling. Here, six example spirit classes as identified by the Beverage Alcohol Manual are examined *(2)*.

Production Stage	Tequila	Whiskey	Neutral Spirits (Vodka)	Gin	Brandy	Rum
Base Material	Agave (complex sugar)	Grain, such as corn, wheat, rye, or malted barley (complex sugar)	Any material, such as corn, wheat, sorghum, potatoes, rice, sugar beets, etc. (sugar can be complex or simple)	Any material, with flavor from juniper berries (sugar can be complex or simple)	Fruit (simple sugar)	Sugar cane (simple sugar)
Processing	Blue agave piñas are manually cut into smaller pieces; after cooking, piñas are shredded, milled, or pressed to extract juice	Roller or hammer mill	Milled or otherwise processed	Milled or otherwise processed	Pressed, shredded, squeezed, or crushed	Pressed, shredded, squeezed, or crushed
Conversion	Steam baked in ovens or autoclaves	Cook the mash; add enzymes	If needed, cook the mash; add enzymes	If needed, cook the mash; add enzymes	None	None
Fermentation	Fermentation of juice or pulp (or wort)	Fermentation of mash; end result is beer (or wash)	Fermentation of mash	Fermentation of mash	Fermentation of juice or pulp (or must); end result is wine	Fermentation of juice or molasses
Distillation	Traditionally batch distilled twice in series	Less than 190 proof; traditionally distilled twice in series	At or above 190 proof	Distillation with or over juniper berries and other aromatics or extracts	Less than 190 proof; traditionally batch distilled twice in series	Less than 190 proof
Maturation/ Aging	Optionally aged days to years in oak containers	Stored at 125 proof or below; stored in charred new oak containers (barrels)	None; filtered with charcoal or other material to remove color, aroma, and taste	None	Stored in oak containers	Stored in stainless steel or oak containers
Bottling (Proof)	At or above 80 proof	At or above 80 proof	At or above 80 proof	At or above 80 proof	At or above 80 proof	At or above 80 proof

but if it is produced outside of the specified region, it cannot be labeled as tequila. The resultant spirit could be labeled "agave spirit" or another alternative.

However the base arrives at the distillery, the base is typically unloaded and mechanically transferred to a storage container. This movement could be done with a conveyor, pneumatically transferred, or gravity fed through chutes. Taking grain as an example, a truck may deliver the grain and use a vendor-owned or owner-owned blower to pneumatically convey the grain through fixed tubing into the top of a storage silo.

The design of the base delivery and storage must keep good manufacturing practices (GMP) and sanitation in mind. Depending on the base material, a shipment could arrive with foreign debris such as metal, stones, or pests. Equipment or procedures should be implemented to prevent foreign debris from entering the storage area.

Once stored, production would draw from the bottom of the storage container to keep the inventory from sitting stagnant. Storage containers should be designed to be fully cleaned, well-sealed, and with the ability to be completely emptied. This will provide a sanitary design and avoid pests, mold, or other unwelcome contaminants.

Processing

The base contains the sugars to be fermented into alcohol but, typically, the sugar is inaccessible to yeast in the base's delivered state. Processing takes different paths depending on the base material and the form of the stored sugar. In Table 1, the classes of spirits are categorized into bases containing complex or simple sugars.

For the bases with simple sugars such as grapes or sugar cane, the base needs to be pressed, shredded, squeezed, or crushed to release a liquid ready for fermentation; often, no extra steps for conversion are required. Distilleries that manufacture from delivered juice or molasses can skip the processing step.

Table 2. Spirit bases comprising starches have different compositions of amylose and amylopectin chains. Source: Adapted from *(3)*.

Starch Source	Amylose (%)	Amylopectin (%)
Common Corn	25	75
Waxy Maize	1	99
High-Amylose Corn	50–75	25–50
Potato	20	80
Rice	20	80
Waxy Rice	2	98
Tapioca, Cassava, and Manioc	17	83
Wheat	25	75
Sorghum	25	75
Waxy Sorghum	<1	>99
Heterowaxy Sorghum	<20	>80

For bases with complex sugars, the base must be made ready for conversion. Bases of grains and potatoes contain complex sugars in the form of starch. Agave for tequila production contains complex sugar in the form of inulin. Both starch and inulin are carbohydrates composed of smaller glucose and fructose molecules.

The goal of processing a starchy base is to increase the surface area of the raw base. The greater the surface area, the more contact with water and enzymes during the conversion step, which increases sugar availability and later alcohol. Specialty vendor equipment is typically purchased to process the base to a state matching the desired specifications of the end user. The resultant size of the processed base is important — too large may limit the starch available to the yeast for conversion and lower yield (amount of sellable product per mass of base material), while too small may cause operational issues if grains clog equipment.

Conversion

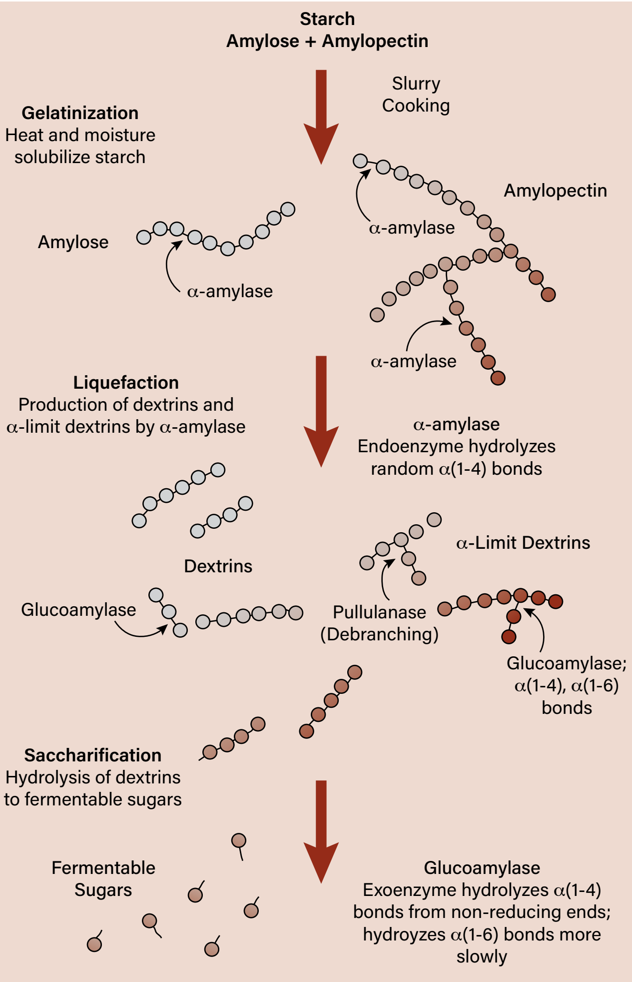
If the sugars are still in a complex form, they must be converted to simple sugars for yeast consumption. Typically, this step involves using heat and/or enzymes to convert carbohydrates to simple sugars.

For agave in tequila production, cut agave hearts are slowly steam-heated in an autoclave or traditional brick oven. According to Jacques *et al.,* "The low pH (4.5) together with the high temperature hydrolyzes inulin and other components of the plant" *(3)*. Inulin is mainly hydrolyzed into fructose. Softened cooked agave hearts are further processed into a pulp. Syrup runoff from the cooking process along with the milled pulp or juice create the sugary wort for fermentation.

The conversion from starch to simple sugars requires more background knowledge. Starch is a carbohydrate composed of chains of carbon, hydrogen, and oxygen. Carbohydrates are named after their chemical composition: carbo (carbon) and hydrate (water) and follow the formula $C_n(H_2O)_n$ or $(CH_2O)_n$. Starch granules are composed of two forms of glucose chains: amylose and amylopectin. Amylose are linear, coiled chains of glucose, and amylopectin are branched chains of glucose. Different grains and potatoes have different percentages of amylose and amylopectin. Starch concentrations consist of about 10–30% amylose and 70–90% amylopectin *(4)*. Table 2 includes examples of amylose and amylopectin percentages in several typical base materials *(3)*.

The chemical structure of the glucose chains is held together with hydrogen bonds. These hydrogen bonds between the starch molecules and adjacent molecules make the starch resistant to water and enzymes at ambient temperature. Imagine flakes of oatmeal floating in room-temperature water; there isn't much of a reaction happening. The beginning of the distillery mashing process is much like making oatmeal at home. Pouring cold water on oats will not provide a thick, delicious breakfast. The water must be hot to allow the starch to absorb the water and gelatinize.

As heat is applied to the starch and water mixture in a distillery, the starch begins to absorb water and expand as the heat breaks the hydrogen bonds of the starch chains. Over time, the enlarged starch granules allow the linear amylose chains to leave the starch granule and mix with the surrounding water, increasing the viscosity of the mash. Eventually, the starch granules expand to the point where they burst like an over-inflated balloon, exposing all the inner glucose chains.



▲ **Figure 2.** Carbohydrates are composed of a mixture of amylose and amylopectin chains. Amylase and glucoamylase enzymes break those chains into shorter molecules during the mash process, which makes simple sugars accessible to the yeast during fermentation. Source: Adapted from *(3).*

The process of mashing adds hot water to ground starch bases, which will result in a thick gelatinous oatmeal-like fluid. This is the desired result of starch hydrolysis in the kitchen when thickening soups or making gumdrops. However, in a distillery, the sugars need to be further cleaved, and the liquid needs to be thin enough to pump; thus, enzymes are added during the conversion step for certain types of spirits (Figure 2) *(3)*. In mash bills containing malted grains, the enzymatic activity could come from naturally occurring enzymes in the malt. Commercial amylase is added or supplemented if natural enzymes are not present in the mash.

The addition of amylase (alpha and beta) enzymes breaks down the liberated long chains of amylose and amylopectin into smaller glucose chains called dextrins. Alpha amylase tolerates higher temperatures and breaks down dextrin chains more randomly and from within the chain (as opposed to the end). This process is also called liquification, as the viscosity decreases with the addition of α-amylase. Beta amylase tolerates lower temperatures and breaks down chains methodically from the end.

Neither alpha nor beta amylase breaks down the branched connections of the amylopectin. A second enzyme, glucoamylase, is added to break the branched dextrin chains of amylopectin into fermentable glucose molecules. The mash is now ready for fermentation.

Heat for conversion can be provided by several methods, including indirect heat using a hot fluid in the vessel jacket, direct heat to the vessel itself from a flame or burner, or direct steam injection to the cooking vessel.

The result of the conversion step is a fermentable fluid. The fluid may contain organic material from the base, such as pulp, skins, husks, etc., or the excess organic matter could be removed at this stage of the process, leaving a liquid with less particulates to be fermented. Once removed, either after conversion, after fermentation, or after distillation, the

Table 3. Starch bases have different gelatinization temperatures. Source: Adapted from *(5).*

Starch	Gelatinization Temperature Range, °F	Gelatinization Temperature Range, °C
Barley	126–138	52–59
Wheat	136–147	58–64
Rye	135–158	57–70
Corn (Maize)	144–162	62–72
High-Amylose Corn	153–176	67–80
Rice	154–171	68–77
Sorghum	154–171	68–77
Potato	136–154	58–68
Tapioca	138–156	59–69
Sweet Potato	136–162	58–72

excess organic matter can potentially be dried and used as animal feed.

As shown in Table 3, starch conversion takes place at temperatures from 126–162°F (52–72°C), while fermentation occurs at lower temperatures of 70–90°F (21–32°C) *(5)*. This means the mash must be heated and then cooled before fermentation begins. The conversion step is likely the first of several steps within a distillery where the temperature of the product needs to be increased or decreased. This creates an opportunity for heat integration in a distillery. For example, hot mash can be used to heat water for clean-in-place (CIP) steps or to preheat the fermented fluid before it is distilled.

Fermentation

At this point, a sugary liquid is ready to be converted into alcohol. Yeast is added to the liquid to metabolize the sugars into alcohol and carbon dioxide. The yeast strain is typically proprietary to the owner. The yeast could be wild or cultured, directly pitched into the liquid, or pre-propagated in a separate vessel.

Fermentation of glucose follows the chemical formula:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The fermentation process is exothermic and the temperature of the liquid must be carefully controlled. It is possible for the fermentation reaction to increase the fluid temperature to a point of irreversible damage to the yeast. Facilities can choose to use jacketed vessels, internal cooling coils, or an external heat exchanger in those cases to maintain a desired temperature. It is also possible for the heat from the exothermic reaction to dissipate into the atmosphere without causing a thermal issue, even without external cooling. Overcompensating with external cooling can slow down the yeast activity, which can also be done intentionally if there are operational outages downstream.

The fermentation vessels could be constructed of wood or stainless steel. They could also be open-top or closed-top. Open-top vessels are popular where a tourism experience is valued by the owner so guests can see the foamy top of the fermenter bubbling. Some owners choose to have open-top fermenters near open windows to allow the local flora to infuse the fermentation mash and add unique characteristics to the final spirit. An open-top fermenter also allows some alcohol to evaporate during fermentation. A closed-top fermenter provides a place for that evaporated alcohol to condense and remain in the fermenter.

At the end of fermentation, the liquid is essentially beer, wine, or hard cider, depending on the base. Producers that sell beer, wine, or hard cider will filter or otherwise clean the product to ensure it is safe for consumers. In a distillery, this low-percentage alcohol by volume (ABV) fluid, often called wash, will be further refined into a spirit.

The other product of fermentation, carbon dioxide, is not to be overlooked. Carbon dioxide is a colorless, odorless, non-flammable gas that is denser than air. In high concentrations (such as within a fermenter) CO_2 presents an asphyxiation risk. Proper ventilation and gas detection should be installed to provide a safe work environment for employees and guests.

Distillation

The distillation process will refine and concentrate the fermented liquid into a spirit (Figure 3). Distillation can be done in batches or in a continuous column still. The concept is the same: Heat the liquid to allow ethanol to boil off. Ethanol has a lower boiling point than water, so water and any impurities, like remaining organic matter, will collect at the bottom of the still while the low-boiling-point components, like ethanol, evaporate.

However, not all the vaporized product is usable as a spirit. The wash boils off in series as “heads,” “hearts,” and “tails.” The most volatile components of the wash, like methanol, boil off first in the heads. Heads can be used for cleaning in the distillery but are dangerous to consume. Next, the hearts boil off, which is the liquid that will eventually be sold as spirits. The last of the vaporized products is

▲ **Figure 3.** Copper stills at a whiskey distiller refine and concentrate the fermented liquid.

called the tails. These are larger molecules that will typically be recycled back into the distillation process to extract any available ethanol. The decision of when to cut between heads, hearts, and tails is made by the owner's master distiller and is often considered both a science and an art.

The vaporized ethanol is condensed, collected, and cooled. Distillation can happen once or multiple times in series to reach the desired proof. The collected ethanol is always clear regardless of the base material.

The distilled spirit leaving distillation is typically measured in proof, which is twice the ABV:

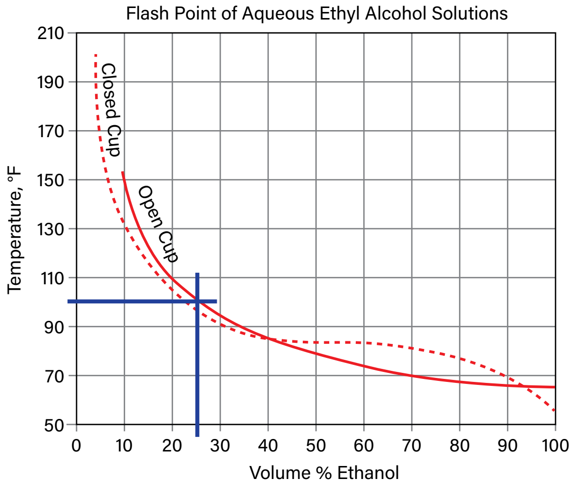
$$2(\text{ABV}) = \text{Proof}$$

For context, the beer leaving the fermenters is usually measured in ABV and can range from 5–12%.

Stills are traditionally constructed of copper. The initial advantages of copper construction were physical. Copper is ductile and malleable, making it relatively easy to construct into various shapes. Copper also has a high thermal conductivity, which provides efficient and even heat transfer, avoiding hot spots. Copper at 68°F has a thermal conductivity of 232 Btu/ft-hr-°F. For comparison, Type 304 stainless steel at 68°F has a thermal conductivity of 8 Btu/ft-hr-°F *(6)*.

More recently, copper has been identified to improve the flavor of the distillate. "Copper aids in the removal of undesirable components, especially sulfur, which imparts an off flavor to the distillate" *(3)*. Modern stills can be a hybrid of stainless steel and copper to take advantage of copper's sulfur reactions with the durability and cost advantage of stainless steel.

Heat provided to distill a spirit comes from steam. Steam boilers that run on natural gas, coal, or fuel oil are available. Sustainable-minded distilleries may opt for boilers that are powered by electricity with the option to run on renewable electricity either generated on-site or coordinated with the utility supplier. In most distilleries, the stills are uninsulated, which allows energy loss to the surrounding atmosphere. It is possible to insulate a still to increase energy efficiency.



▲ **Figure 4.** An ethanol mixture of approximately 25% alcohol by volume (ABV) has a flash point of 100°F, making the mixture eligible for Process Safety Management (PSM) compliance if 10,000 pounds or more is stored. Source: Adapted from *(8)*.

The U.S. Occupational Safety and Health Administration's (OSHA's) Process Safety Management (PSM) standard applies to "a process which involves a Category 1 flammable gas (as defined in 1910.1200(c)) or a flammable liquid with a flashpoint below 100°F (37.8°C) on-site in one location, in a quantity of 10,000 pounds (4,535.9 kg) or more" *(7)*. This excludes flammable liquids stored in atmospheric storage tanks remote from the process but includes collective volume within a process.

Let's assume the distillate from the final distillation run is 140 proof or 70% ABV. A solution of 70% ethanol has a flash point around 70°F, which is below the PSM criteria of 100°F. If 10,000 pounds (or ~1,350 gallons) of 140-proof spirit is stored in one or collectively in several containers, the system qualifies for OSHA's PSM. The containers could include the top of the still, condensers, interconnecting piping, and storage tanks (like a bottling or proof tank) close to the still.

As shown in Figure 4, once ethanol reaches beyond ~25% ABV (50 proof), the flash point of the mixture falls below 100°F *(8)*. If greater than 10,000 pounds of the mixture is present in the system, the system qualifies for OSHA PSM.

OSHA has provided an interpretation letter that states, "Although distillers are required to comply with the PSM standard, OSHA is not enforcing and will not enforce the PSM standard with respect to processes in distilleries and their related facilities…, except in the event of a fatality or catastrophe involving a process that uses ethyl alcohol in a distillery or related facility" *(9)*. However, the absence of enforcement does not mean an absence of risk or hazard. Abiding by safety standards is responsible engineering and operational practice.

Maturation

After distillation, the spirit can take several paths depending on the desired end product. Vodka is filtered to remove any color, aroma, or flavor and can then be bottled. Gin and blanco tequila also do not require maturation and can be bottled after distillation. Blanco tequila can be optionally aged for two months or less before bottling.

Whiskey, brandy, rum, and aged tequila all require maturation. Typically, this is done — and required for some spirits — in oak containers (Figure 5). Stainless steel can also be used to mature spirits. Maturation allows chemical reactions to take place within the container, which develops color, aroma, mouthfeel, and flavor. For further reading on the chemical interactions happening within the barrel during bourbon aging, see Ref. 10.

The chemical compounds developed either in fermentation or maturation are called congeners. The congeners contribute flavor and aroma to the distillate but can also add to a hangover. In a study comparing drinking low-congener (vodka) and high-congener (bourbon) alcohol, the study found "beverage congeners in bourbon versus vodka did significantly increase the intensity of hangover that was felt, consistent with results from studies in the 1970s" *(11)*.

During maturation, volume in a barrel might be measured in wine gallons or proof gallons. Wine gallons are the total volume in a barrel or other container independent of proof. Proof gallons refers to the equivalent volume of ethanol if it were converted to 50% ABV (or 100 proof) wine gallons:

$$\text{Proof Gallons} = \text{Wine Gallons} \times (\text{Proof}/100)$$

If a whiskey barrel is full of 50 gallons of 120-proof spirit, the contents could be referred to as 50 wine gallons, or 60 proof gallons.

Bottling

Before bottling (and possibly before barreling), spirits are mixed with water to reach a specified proof point. Water used to cut the spirit is typically filtered to a high quality, sometimes employing reverse osmosis (RO) filtration.

The process of bottling and labeling can range from fully manual to fully automated. Some small facilities make bottling an event and invite the public for help. Depending on the size of the distillery and available labor, various levels of automation can be incorporated into bottling as well as the rest of the spirit making process.

Conclusion

From grain-receiving to bottling, spirits production employs many aspects of chemical engineering. Next time you join a distillery tour or raise a glass in celebration, take an extra minute to appreciate all the reactions, thermodynamics, and separations that led to your libation.

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▲ **Figure 5.** Bourbon barrels age in a rickhouse to develop the color, aroma, and flavor characteristic to the spirit.

Literature Cited

1. **Alcohol and Tobacco Tax and Trade Bureau,** "Federal Alcohol Administration Act," U.S. Code Title 27 Ch. 8, https://uscode.house.gov/view.xhtml?path=/prelim@title27/chapter8&edition=prelim (accessed Mar. 31, 2025).
2. **Alcohol and Tobacco Tax and Trade Bureau,** "The Beverage Alcohol Manual (BAM) A Practical Guide," U.S. Dept. of the Treasury, Vol. 2, Chapter 4, https://www.ttb.gov/system/files/images/pdfs/spirits_bam/complete-distilled-spirit-beverage-alcohol-manual.pdf (April 2007).
3. **Jacques, K. A., *et al.,*** "The Alcohol Textbook 4th Edition," Nottingham University Press, Nottingham, U.K. (2003).
4. **Ogori, A. F., and A. Taofeek,** "Starch Chemistry and Application," *Journal of Food Technology and Preservation,* **6** (6), #130 (2022).
5. **Strickland, M.,** "Mash: Chemistry 101," *Distiller,* https://distilling.com/distillermagazine/mash-chemistry-101 (Dec. 27, 2019).
6. **Engineering Toolbox,** "Thermal Conductivity of Metals and Alloys: Data Table & Reference Guide," https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html (accessed Mar. 31, 2025).
7. **Occupational Safety and Health Administration,** "1910.119 – Process Safety Management of Highly Hazardous Chemicals," U.S. Dept. of Labor, https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.119 (accessed Mar. 31, 2025).
8. **Equistar Chemicals, LP,** "Ethyl Alcohol Handbook," 6th Edition (2003).
9. **Occupational Safety and Health Administration,** "OSHA Enforcement Policy of the PSM Standard Distilleries and Related Facilities in SIC 2085," U.S. Dept. of Labor, https://www.osha.gov/laws-regs/standardinterpretations/2003-03-14 (Mar. 14, 2003).
10. **Demoranville, L., and P. Heist,** "The Chemistry of Bourbon," *Chemical Engineering Progress,* **117** (8), pp. 40–45 (Aug. 2021).
11. **Rohsenow, D. J., *et al.,*** "Intoxication with Bourbon versus Vodka: Effects on Hangover, Sleep and Next-Day Neurocognitive Performance in Young Adults," *Alcohol Clinical & Experimental Research,* **34** (3), pp. 509–518 (Mar. 2010).