Farm Scale Alcohol Production

The Iowa State University Ethanol Distillery

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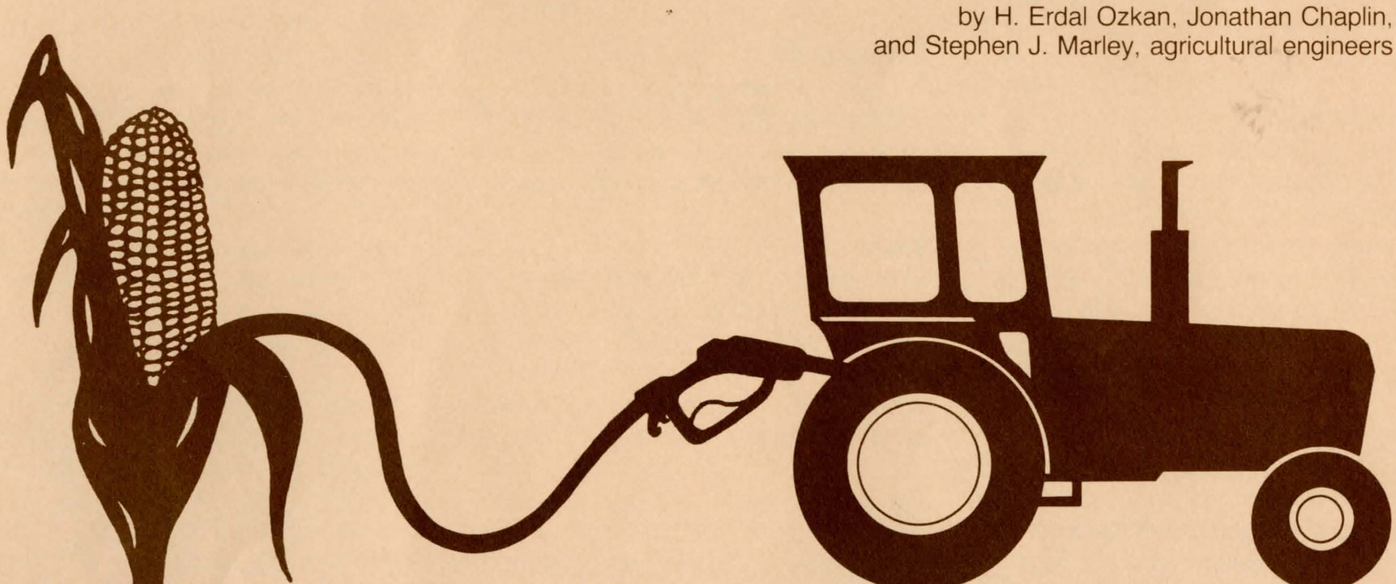

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Ethanol Production on the Farm

High petroleum prices and possible shortages of petroleum fuels have created high interest among farmers in producing energy from renewable sources readily available on the farm. One way Iowa farmers can become energy independent is to produce ethanol (ethyl alcohol) from corn to power their farm machinery.

Although the principle of making alcohol from grain has been around a long time, the technology and equipment to produce fuel-grade alcohol on the farm have not been available until recently. Iowa State University (ISU) researchers are investigating the possibilities of using farm-produced ethanol as an alternative fuel. When alcohol fuels research began at ISU, there was only one other university research unit producing alcohol in the United States. The ISU distillery has played a major role in demonstrating the equipment required for setting up a farm-scale ethanol still to farmers in Iowa and elsewhere in the country.

Although the information presented in this publication relates to the ISU ethanol distillery, the process outlined for making ethanol is applicable to most farm-scale stills.

Construction of the still was started in the summer of 1978 after receiving a grant from the Iowa legislature "for the purpose of designing and assembling a *farm-scale* plant for the production of ethanol from grain and waste products readily available on a farm, and for determining the management and operational requirements of the plant."

The distillery was designed and built by agricultural engineering faculty and staff and became operational in August 1979. Preliminary trials indicated a need for a series of modifications, and the distillery came into full production in August 1980. Since then, almost 1,500 gallons of 180-proof ethanol have been produced.

When all steps in alcohol production are completed efficiently, 2.5 gallons of anhydrous (200-proof) ethanol can be produced from one bushel of corn. Production of anhydrous ethanol at small-scale alcohol plants is difficult and not practical. For these reasons, the ISU distillery, designed to represent small-scale plants, usually produces 180-proof ethanol.

Distillery Size

The distillery size was chosen so that two batches of ethanol could be produced each week. Each batch processes 40 bushels of corn. This should produce 11,200 gallons of 180-proof ethanol annually.

Most farmers, however, will not be able to operate alcohol stills year-round. Labor demands and field operations during the crop production season may force them to shut down their alcohol plants. It is more realistic to expect alcohol production for only half the year. If operated twice weekly for 25 weeks, 5,200 gallons of 180-proof ethanol can be produced in a plant the same size as the ISU distillery. This should satisfy the liquid fuel needs of a 200-acre corn farm.

Equipment

The ISU distillery consists of two 1,600-gallon tanks, a 10-inch-diameter distillation column, a condenser, a heat exchanger, and various pumps.

Tanks

Although each tank is large enough to process 40 bushels of corn in a batch, only one tank is equipped for cooking. The cooking tank is also used for mash fermentation. The second tank is used to store cooling water for reuse.

The cooking tank has a hopper-bottom and is fitted with a hydraulically-driven stirring turbine. Cooking is accomplished by injecting steam from the ISU physical plant directly into the mash via a circular sparge ring located at the bottom of the cooking tank. The steam flow rate is measured by a rotameter mounted in the steam supply line.

Distillation Column

A single 10-inch-diameter column is used for complete distillation. The lower half of the column (stripping section) is designed to strip alcohol from the fermented mash. The upper half of the column (rectifying section) is used to increase the concentration of alcohol in the end product (alcohol and water).

Three configurations have been used to evaluate column performance. The original height of the column was 15 feet. This column was defined as the *short-plate* column and contained 22 sieved plates. Spacing between plates is 8 inches. Twelve of the plates are located in the stripping section. Beer enters the column at the twelfth plate from the bottom. The plates in the stripping section have ½-inch-diameter holes providing an open area of 30 percent. Total height of the stripping section is 8 feet.

The 7-foot rectifying section has 10 plates. The diameter of the holes in these plates (3⁄16 inch) is smaller than those in the stripping section and they are spaced closer together. This provides greater open area (48 percent) on the plates. The other difference between the plates in the two sections is that 1 ⅜-inch-diameter downcomers are brazed into each plate in the rectifying section. Downcomers limit the maximum liquid depth on each plate to ⅝ inch. Once the depth of liquid on the plate reaches this point, liquid overflows to the next lower plate through these downcomer pipes. Figure 1 illustrates the configuration of sieve plates in the rectifying section.

The first modification made on the column was the addition of eight more plates to the top of the column. Additional plates increased the column height by 5 feet (from 15 to 20 feet). No other changes were made on the column which is known as the *long-plate* column.

The third major modification made on the column was replacement of plates on the rectifying section of the column with packing material. All plates starting from the second plate above the entry point of beer to the column were replaced by raschig rings, a commercial ceramic packing material . This column is classified as the *long-packed* column.

Design characteristics of stripping sections in long-plate and long-packed columns were the same as those in the short-plate column.

Condenser

The original condenser was a locally constructed tube and shell unit. Top and bottom sections and a tube assembly were added to a standard 30-gallon drum. As shown in fig. 2, the top and bottom sections of the shell are connected by thirty-two ¾-inch-diameter pipes. Cold water enters the bottom section of the condenser, travels through the pipes, and leaves at the top. At the same time, alcohol vapors enter the middle section and are condensed to liquid when they contact the cold surface of pipes connecting the top and bottom sections.

Because of its limited capacity, this condenser is no longer being used. It has been replaced with a commercially available multiple-pass heat exchanger which is constructed from copper and steel. The velocity of cooling water is increased in this multiple-pass condenser, lowering the resistance to heat transfer and thus increasing the efficiency of the unit. This condenser is designed to reduce scale deposits which tend to accumulate with intermittent operation. This improves both condenser efficiency and life. The current condenser is shown in fig. 3.

Heat Exchanger

A tube-in-tube heat exchanger is used to control temperature of mash at any given time. Mash is pumped through the inner tube. When the temperature of the mash has to be reduced, cold water circulates through the outer tube. Steam is circulated through the outer tube to raise the temperature of liquid pumped into the heat exchanger.

Pumps

Pumps are necessary to move materials from one unit of the distillery to another. The ISU distillery operates five pumps. They are used to pump mash to the heat exchanger, beer to the column, stored water to other units, low-grade alcohol back to the column (reflux pump), and to discharge stillage from the column to the settling tank.

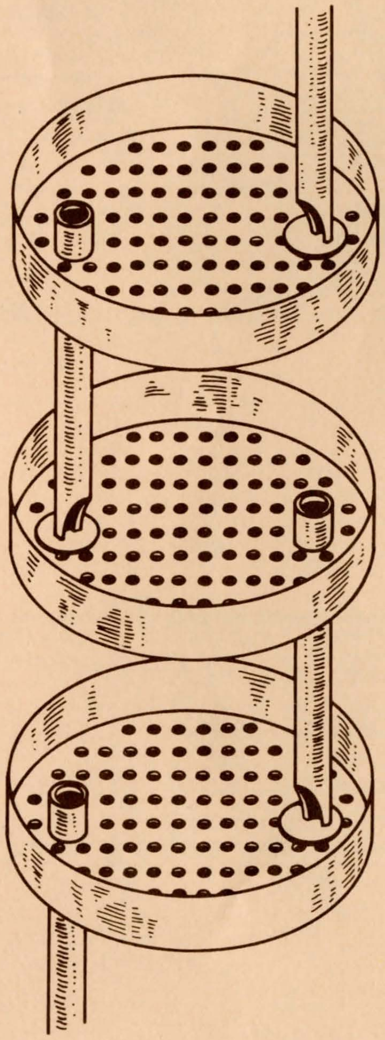

Fig. 1. Sieve plates of distillation column in the rectifying section.

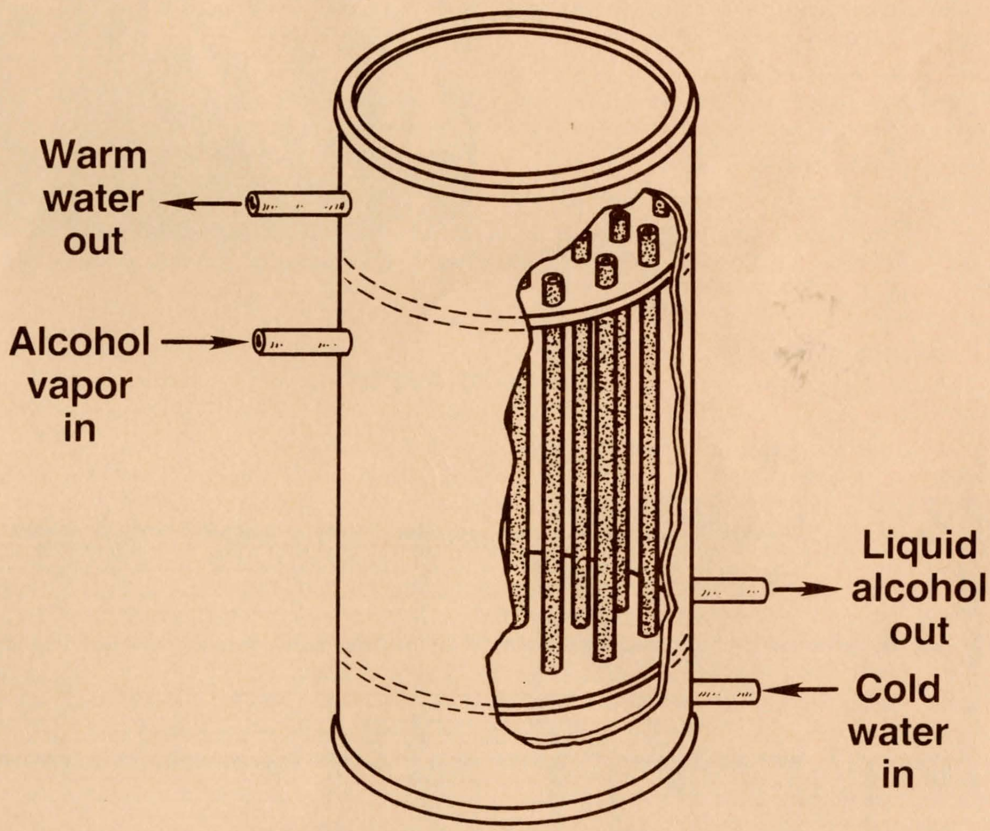

Fig. 2. The original condenser unit.

The distillation column and all pipes are insulated. Temperatures are measured using copper constantan thermocouples located at 40 different points in the distillery. Thermocouples are connected to a 40-position switch and a proprietary digital display. A general overview of the ISU ethanol distillery is illustrated in figs. 4 and 5.

The Process

Ethyl alcohol can be produced from any agricultural product that contains starch, sugar or cellulose. However, conversion of cellulose to ethanol is not a practical process for small plants. Since corn is the main starch crop produced in Iowa, it is used as the feedstock to make ethyl alcohol at the ISU distillery.

Producing ethyl alcohol from starch crops is a simple process as illustrated in fig. 6. There are three major phases of ethanol production from corn or any other starch crop: (1) conversion of the starch to fermentable sugars, (2) fermentation of sugars to ethanol, and (3) separation of ethanol from the water and nonfermentable materials. Although the concept is simple, the process requires some knowledge of physics, chemistry, and microbiology, and knowledge of precise timing of each operation. Figure 7 is a schematic illustration of the complete ethanol production process and material flow in the ISU distillery. The detailed information concerning the process is as follows.

Formation of Fermentable Sugars

During this process, the starch in the grain is converted into sugar. This is done by milling the grain, diluting it with water, cooking the mash, and adding enzymes to this mixture.

Milling

Milling corn to a fine meal exposes starch granules and keeps them suspended in water. In such formation, starch granules easily absorb

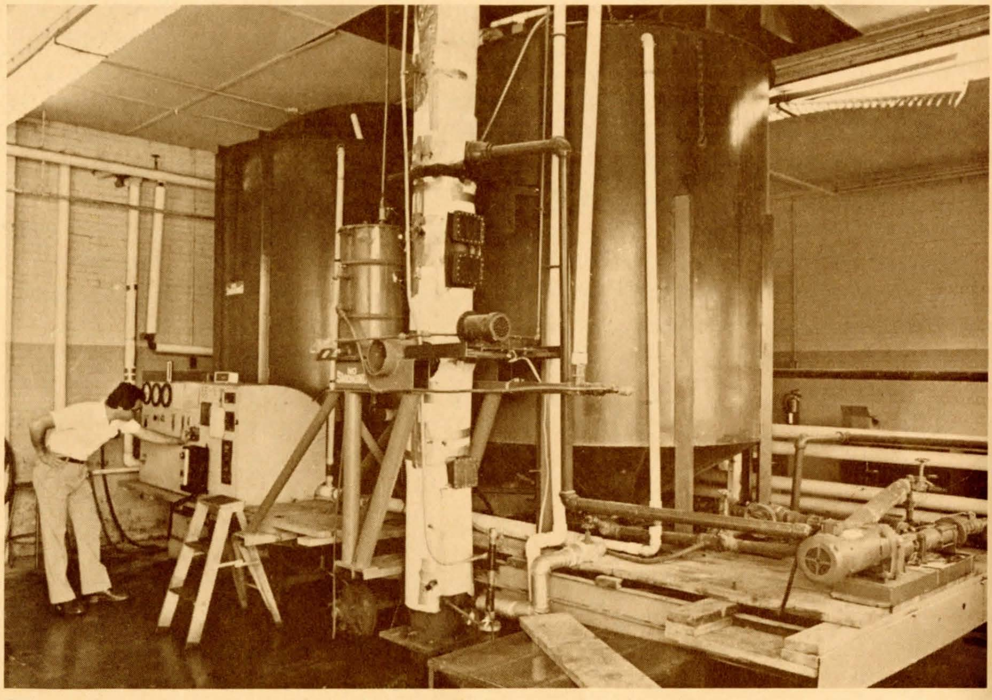

Fig. 4. Overview of the ISU ethanol distillery.

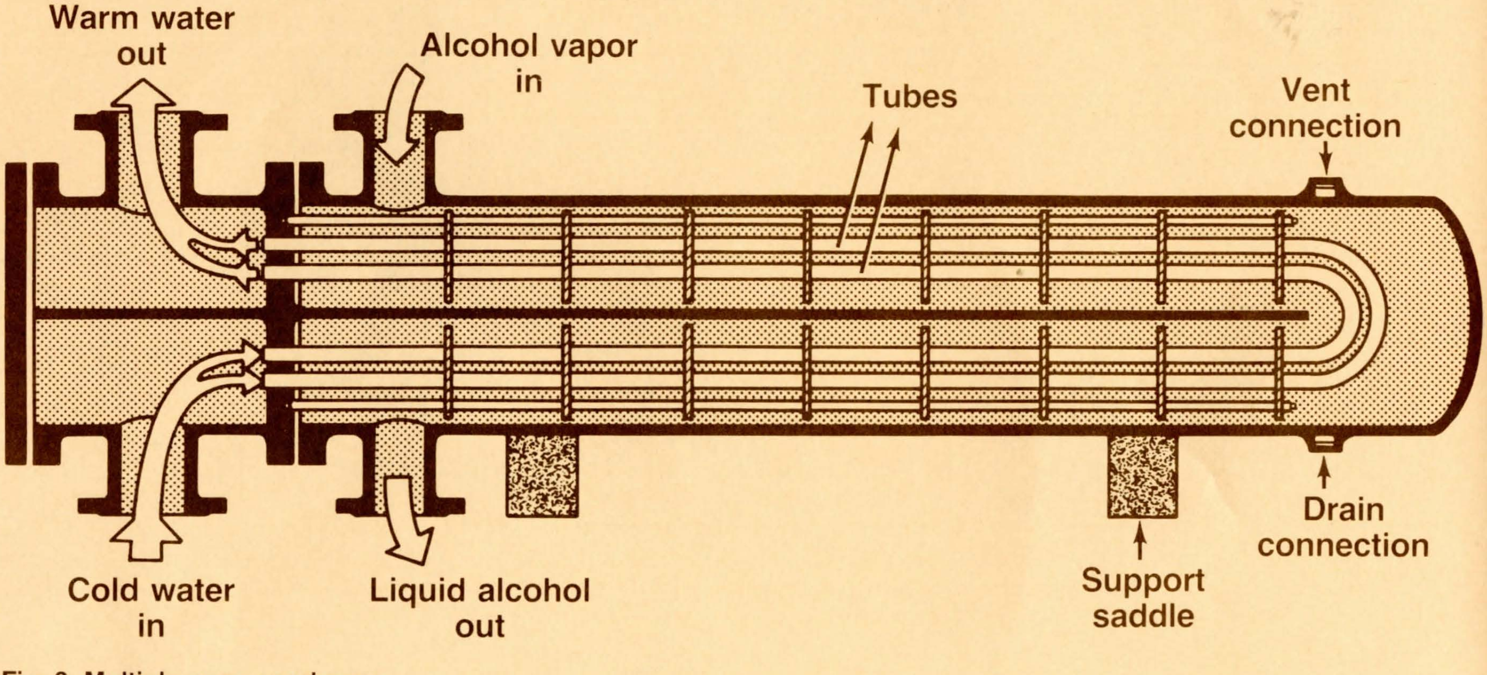

Fig. 3. Multiple pass condenser.

water.Grain that is ground too fine makes it difficult to separate the solids from the liquid, causing a possible loss of the valuable distiller's grain.

Slurrying and liquefaction

Ground corn is mixed with approximately 10 gallons of water per bushel of corn to form a mash. Next, the enzyme alpha-amylase is added to the mash to prevent it from forming a stiff semi-solid and to convert starch into complex sugars. Since the pH (acidity level) of the mash must be correct for optimum enzyme performance, the pH is adjusted to the enzyme manufacturer's recommendation before adding the alpha-amylase. At the ISU distillery, the pH is adjusted downward (more acid) by adding sulphuric acid and upward (less acid) by adding sodium hydroxide.

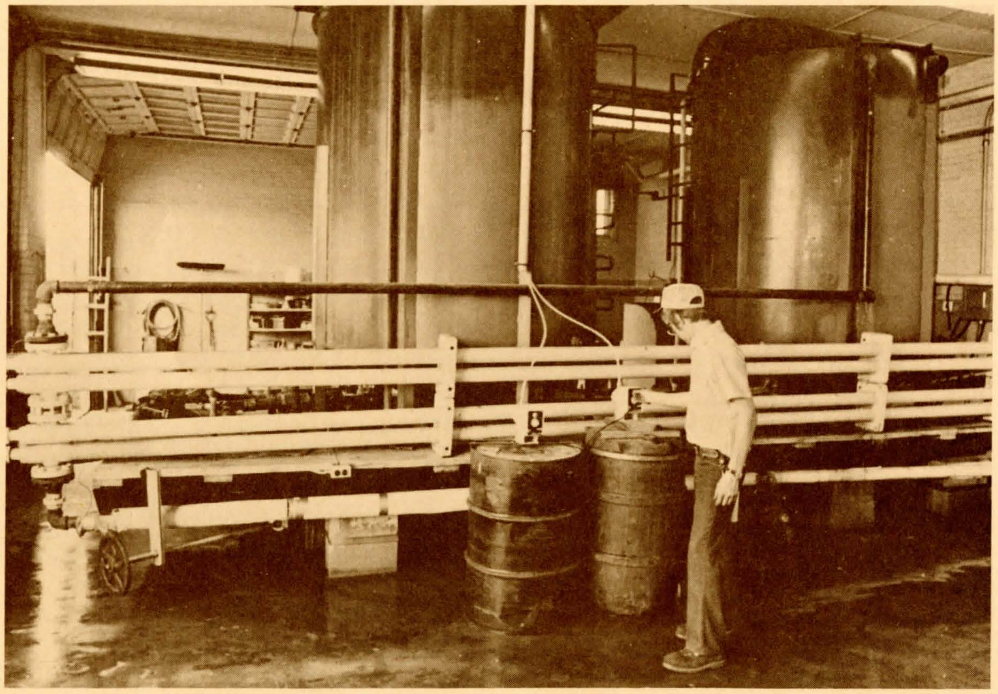

Fig. 5. Cooking and fermentation tank, water storage tank, and heat exchanger unit of the ISU ethanol distillery. Chemicals (acids or bases) from the barrels are being added to the cooking tank to adjust the pH level of the mash.

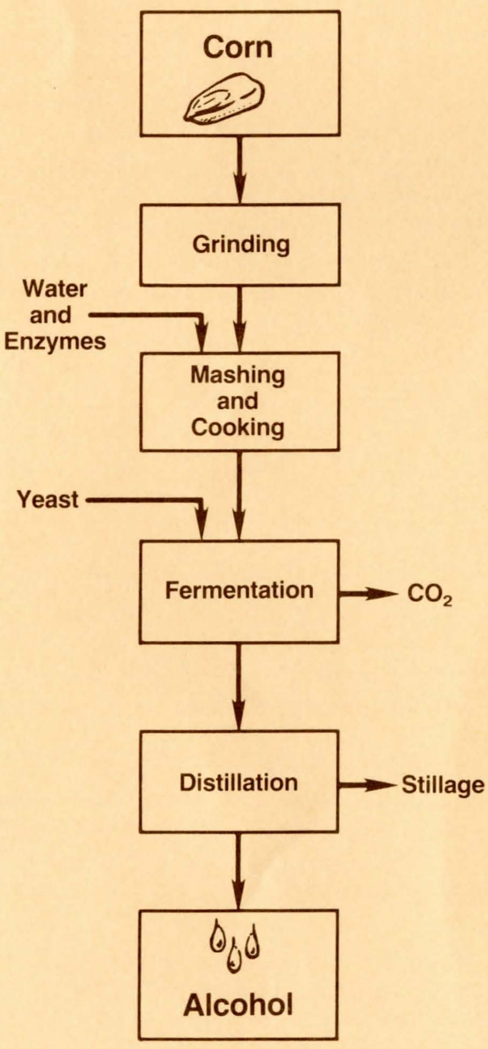

Fig. 6. Schematic of ethanol production process.

Steam is injected into the cooking tank to heat the slurry to a temperature of 205° F (96° C) and held at that temperature for a minimum of 30 minutes. Mash is agitated continuously during the cooking process to ensure enzyme contact with all of the starch.

Saccharification

After liquefaction is complete, mash is cooled to 140° F (60° C). This is accomplished by diluting it with cold water (about 10 gallons per bushel of corn) and circulating it through the heat exchanger. This additional water brings the concentration of solids in the mash down to 20 percent.

At this time, a second enzyme, gluco-amylase, is added to the mash. This enzyme breaks the complex sugars into glucose, a simple sugar, which now can be fermented to ethanol. Before adding this second enzyme, the pH of the mash must again be adjusted to the manufacturer's recommendation. Gluco-amylase needs a pH level of 3.8 to 4.5 to function properly. Agitation of the mash is continued.

The mash temperature is then allowed to drop slowly until it reaches a temperature that is optimum for yeast fermentation. This is between 85° and 90° F (29° and 32° C) for most commercial yeasts. Cooling is accomplished by using the heat exchanger. No water is added to the mash during this step to avoid excessive dilution.

Mash Fermentation

When mash is cooled, a test is performed to check starch conversion to sugar by using the Iodine Starch Test. If the test result indicates that all starch is converted to glucose, the mash is innoculated with yeast to initiate the second phase, fermentation. Fermentation is allowed to proceed for 2 to 3 days. During that time, the yeast converts glucose into ethanol and carbon dioxide while releasing some heat energy. Carbon dioxide bubbling through the mash provides sufficient agitation so no mixing is required. If the temperature of the mash exceeds 85° F (29° C), provisions must be made to cool the mash. Excessive temperature adversely affects metabolism of the yeast cells. They become inactive and stop producing alcohol from sugar.

Two to 3 days are required for the fermentation of saccharified starch because enzymatic hydrolisis of complex sugars is continually occurring during fermentation and replenishing glucose in the substrate. Disappearance of carbon dioxide bubbles is a good indication of fermentation being complete, but a test to determine sugar content of the mash is performed.

The mash tank is covered to reduce mash-oxygen contact. If this is not done, bacteria in the presence of oxygen may oxidize alcohol to acetic acid. A small opening must be provided for carbon dioxide to escape.

Distillation
By definition, distillation is the process of separating the more volatile components of a mixture from nonvolatile or less volatile components.

Under atmospheric pressure, ethanol boils at 173° F (78° C), while water boils at 212° F (100° C). When water and ethanol mix, the boiling point falls between these two figures, depending on the relative volumes of ethanol and water in the mixture. More alcohol in the mixture lowers the boiling point, while more water raises it. At an ethanol concentration of 95.6 percent by weight (194-proof), a constant boiling mixture (an azeotrope) forms, making further separation of ethanol impossible when distillation is performed under atmospheric conditions. For this reason, ethanol cannot be concentrated to more than 95.6% by weight by the distillation process used at the ISU distillery.

After fermentation is complete, as indicated by the absence of reducing sugars in the beer, and the alcohol content is approximately 7 to 8 percent by weight, the third phase, distillation, can commence. Before starting the distillation process, the beer (which contains water, alcohol, and remaining solids) is preheated to a temperature above 140° F (60° C). This is accomplished by pumping beer through the tube-in-tube heat exchanger where heat is derived from steam. Beer preheating is controlled by adjusting the steam valve. Preheating the beer improves over-all column efficiency.

In the ISU plant, the preheated beer feed enters the distillation column at the twelfth plate from the bottom. Steam is sparged into the bottom of the distillation column to provde energy for separation of alcohol from water and solids that remain in the beer. The steam, contacting the beer as it falls through the plates in the stripping section, vaporizes alcohol and some of the water. In a plate-type column, the temperature at each plate in the rectifying section is slightly lower than at the plate below it, resulting in a temperature decrease from bottom to top in the column. This way, most of the alcohol remains vaporized and rises, while water vapors condense in the cooler upper portion of the column and flow back to the bottom of the column. There is an enrichment of the alcohol vapors as they pass up the column from plate to plate. Vapors leaving the column at the top are mostly alcohol. These vapors then go through the condenser and turn to liquid alcohol which is collected in a storage tank.

The first condensate collected still contains a high percentage of water. All of this condensate is returned (refluxed) to the column at the top by a variable-speed gear pump to improve the quality of the alcohol collected. The reflux rate is changed until a stable temperature of approximately 174° F (79° C) is reached at the top plate in the column. Alcohol quality is controlled by the reflux rate. Once the column has reached a steady temperature gradient, alcohol may be drawn off and stored. A hydrometer is used to measure alcohol content of the final product.

All the beer is passed through the column with no attempt at solids removal. The bottoms product, mostly water and remaining solids, is drawn out of the bottom of the column and into a settling tank by a float-controlled pump.

Findings

A maximum of 2.62 gallons of 200-proof ethanol can be produced from one bushel of corn at 15.5 percent moisture content (wet basis). In reality, it is impossible to achieve such high theoretical yields. Not all of the starch can be converted to glucose and 100 percent conversion of glucose to ethanol is not possible. Even in more efficient large-scale commercial alcohol plants, not more than 95 percent conversion of starch to ethanol is achieved.

Our yield to date has been 2 gallons of 180-proof ethanol per bushel of corn. The production capacity of the still has been 10-12 gallons of 180-proof ethanol per hour.

Fermentation has not been a problem. We have used fresh yeast for each batch. Both baker's and brewer's yeast performed equally well. Although the fermentation process produces heat, we have not had to cool the mash during fermentation in cold seasons. This may be because our fermentation tank is not insulated. During summer, we have had to cool mash in the fermentation tank to a proper fermentation temperature only once.

Our major problems with distillery operation have been in the distillation phase. We have had difficulty both in stripping all of the alcohol out of the beer and in achieving a high proof ethanol. In an effort to maximize alcohol recovery, we put the solids through the column in a mixture with liquid. With the fine grind we used, column plugging occurred twice.

No differences were found in the quality of ethanol from the three different columns investigated. The longer columns were more stable to control. Over-all, the plate columns performed satisfactorily. The long-packed column was susceptible to clogging and is not reommended for unfiltered beer feeds.

One problem we have not resolved is loss of alcohol with the bottoms product. Analyses of bottoms product showed 0.5 to 1.0 percent ethanol. Stripping all the alcohol from the beer is not feasible, but an alcohol content as low as 0.5 percent in the bottoms product represents 7 percent of the total ethanol produced during fermentation.

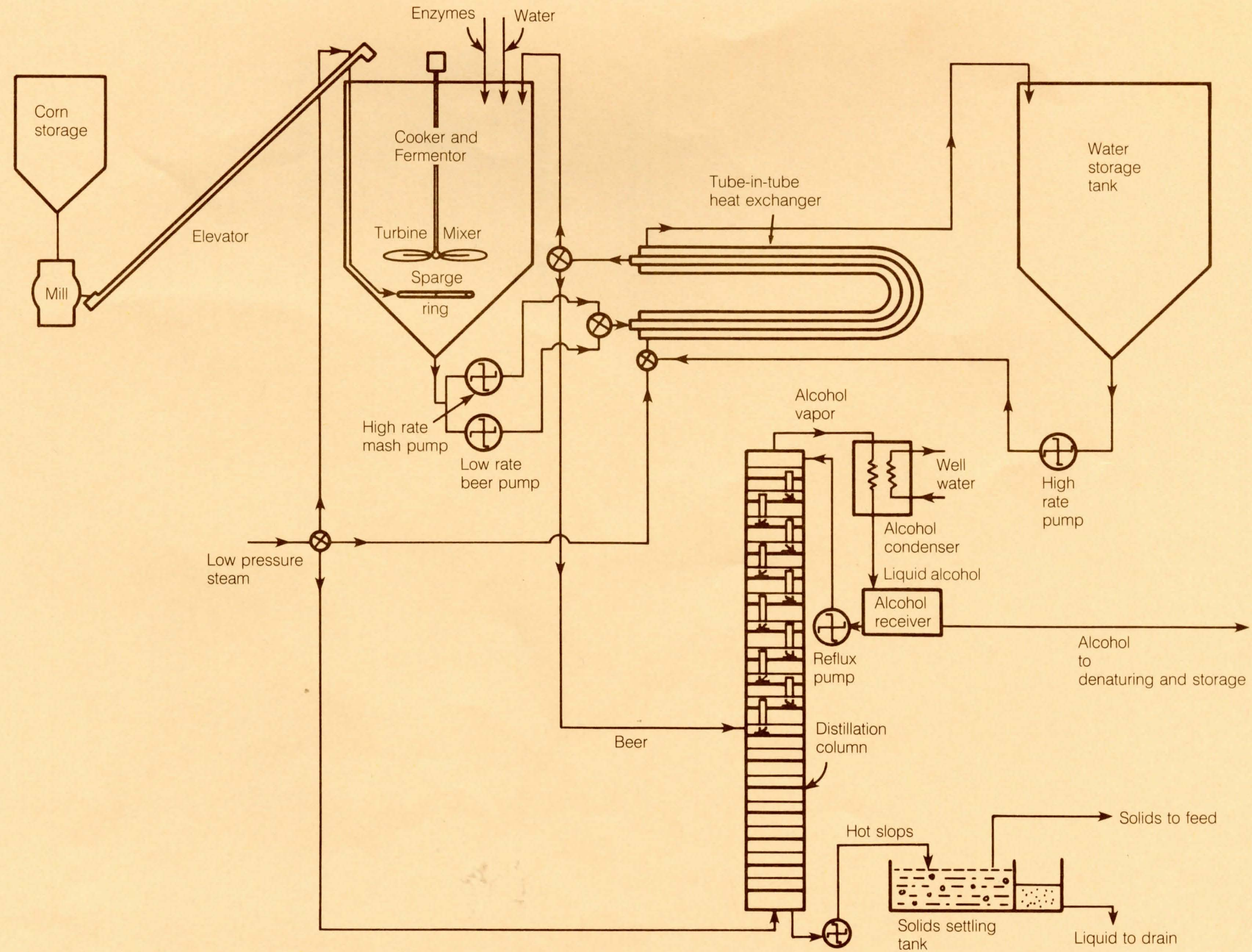

Fig. 7. Flow diagram of the ISU distillery in operation.

Energy Balance

Data were collected to determine the response in separation and energy requirement for three types of distillation columns. Unfortunately, energy requirement equations could not be generated for the long-packed and long-plate columns due to large unexplained variations in data for similar operating conditions.

As shown in table 1, the overall energy balance of the ISU ethanol plant with the short-plate column can be positive. When the plant operates under the best conditions, 1.51 units of energy can be recovered from the ethanol and distilled grain for every unit of energy used to produce the corn and convert it to ethanol and wet distillers grain. However, the net energy balance can be drastically reduced and become negative if the distillation column is operated under poor conditions such as low beer alcohol concentrations, high operating temperatures, low feed rates, and high reflux ratios. Operation of small distillation columns must be closely controlled, ensuring a beer of sufficiently high quality at the lowest reflux ratios, and top-plate temperature set at 173° F (78° C) to reduce energy consumption.

Table 1. Energy balance of ethanol production using a short-plate column.

Inputs	Low distillation energy (Btu/gal)	High distillation energy (Btu/gal)
Farm energy input[1] Non-irrigated corn	29,800	29,800
Transportation[1]	3,900	3,900
Plant energy input		
Mashing, cooking, and conversion	14,700	14,700
Distillation	23,700	65,000
Fermentation	0	0
Electricity	6,400	6,400
Total	78,500	119,800
Outputs		
Ethanol	84,600	84,600
Bottoms product[1]	34,100	34,100
Total	118,700	118,700
Energy balance	40,200	−1,100
$\text{Gain} = \frac{\text{total output}}{\text{total input}}$	1.51	0.99

[1]From Ofoli & Stout, "Ethyl Alcohol Production for Fuel: Energy Balance." *Agricultural Energy* Vol. 2, pp. 292-298. American Society of Agricultural Engineers publication 4-81. St. Joseph, Michigan, 1981.

Future Research Objectives

While the ISU distillery succesfully converts corn to fuel alcohol, some problems remain. Labor requirements are high, alcohol yield and proof are often low, and energy required for distillation is still too high. The major objectives of our continuing research are to develop a continuous cooking and distillation process to replace batch processes; to investigate the effectiveness of vacuum and other distillation techniques in increasing the proof of the alcohol produced; and to develop an automatic control system to reduce labor and management inputs.

Currently, ISU is investigating the feasibility of a continuous throughput ethanol plant. This new plant will have a capacity of 50 gallons of 180-proof ethanol per day. If operated 24 hours a day throughout the year, the alcohol produced from the plant will be enough to satisfy the liquid fuel requirements for production of 1,300 acres of corn. The proposed plant could be scaled up for small groups of farmers for cooperative ethanol production.

The research will also investigate the clogging characteristics of small distillation columns. This will provide information concerning the optimal screen size for solids separation.

Other Publications

This publication was prepared to describe how the ISU distillery has been operating. Information concerning other aspects of alcohol fuels may be found in the following ISU Extension publications:

Pm-933a—Corn Stillage as a Feed Source for Livestock
Pm-933b—Alcohol as a Farm Engine Fuel
Pm-933c—The Ecomonics of Grain Alcohol as a Motor Fuel
Pm-933d—Alcohol from Crops - Crop and Soil Management Considerations
AE-2026—Operation of a Spark-Ignition Engine with a Range of Ethanol and Water Mixtures
Pm-1020—Facts about Fuel Alcohol Production
Pm-1021—Facts about Using Alcohol in Engines

File: Engineering 2

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