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Energy Reduction in the Production of Ethanol by Membrane Dehydration

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Abstract: Distillation/dehydration represents the largest fraction of the energy used in the production of ethanol. The Siftek™ technology introduced in this paper carries the potential of reducing energy consumption of distillation/dehydration by up to 50% through the single pass removal of water from the water/ethanol stream at the beer column outlet, using a novel membrane process. For a modern corn-based ethanol plant, this is equivalent to 7.0 US\$/gal, or 1.8 US\$/L.

Siftek™ is a novel polymeric membrane that can operate continuously in the vapor phase and in the presence of high water concentration. The hollow fiber membranes are made of a proprietary polyimide blend that offers high water/ethanol selectivity and water permeance. The water/ethanol vapor mixture is introduced at the beer column operating pressure on the bore side of the hollow fiber module. The water permeate stream is condensed and the steam latent heat is recovered. A vacuum provides the driving force between the bore side and the shell side of the membrane. The technology has been demonstrated in the field at a capacity of 1200 kg/day (2600 lbs/day) of vapor feed with an ethanol content varying between 75 and 90 wt% at one of the Greenfield Ethanol Inc plants in Tiverton, Ontario, since August 2006.

The presentation will include a detailed description of the technology, the results from the field demonstration unit, scenarios for retrofitting into existing or new green-field ethanol plants, and a summary of the energy savings and projected pay-back calculations.

Keywords: Ethanol, dewatering, refining, membranes, vapor separation

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INTRODUCTION

The use of ethanol as a fuel has been growing exponentially around the world, with global production now exceeding 13 billion gallons/year (50 million m³/y). In 2006, the US production approached 5 billion gallons (19 million m³) making it for the first time the largest producer in the world, ahead of Brazil. The US demand for ethanol in 2006 was stimulated by the mandatory replacement of methyl tertiary butyl ether (MTBE) as a gasoline additive. Going forward, ethanol is seen as a replacement for fossil fuels, decreasing the dependency on imports and reducing the emission of green house gases. While it is recognized that the amount of ethanol that can be produced from corn is limited (US estimates vary from 10–15 billion gallons/year), it is anticipated that the development of processes based on cellulosic materials will provide an almost infinite source of feedstock to meet the American Government objective of 20/10, i.e., replacing 20% of gasoline with bio-ethanol over the next 10 years.

After corn, steam is the most important cost in the production of ethanol. Based on an analysis of the dry milling process, (7) estimated that steam represents approximately 15% of the total production cost (base case) estimated at US\$1.61/gal (0.43 US\$/L), before credits for any by-products.

The technology introduced in this paper carries the potential of reducing energy consumption for distillation/dehydration by up to 50% through the single pass removal of water from the water/ethanol stream at the beer column outlet, using a novel membrane process. For a large ethanol plant (42 million gal (160,000 ML) per year), this translates into a reduction of greenhouse gases (GHG) of 21,000 t/year, which is equivalent to over 2 million gallons of gasoline.

The data presented is for ethanol produced from corn, but the technology is also applicable, with similar benefits, to other feed stocks.

The use of membrane in the processing of ethanol is not new. Pervaporation (3) or vapor permeation (5) have been proposed as a replacement of the dehydration step (i.e., in replacement of the molecular sieves to break the azeotrope). These solutions carry limited potential for energy reduction as the bulk of the energy is spent in the distillation process itself.

BACKGROUND

The Siftek™ Membrane and System

Siftek™ is a hydrophilic polymer membrane that can be used to dry ethanol in the vapor phase, in a continuous process illustrated in Fig. 1.

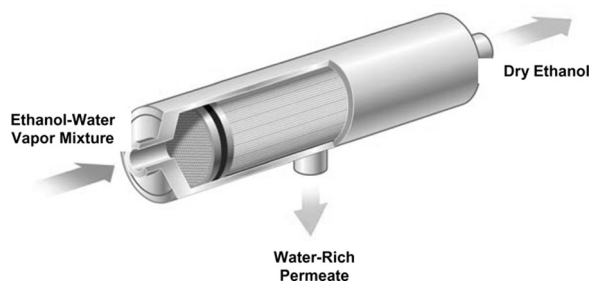


Figure 1. Conceptual operation of the Siftek™ membrane for the drying of ethanol.

The ethanol-water vapor mixture is fed to the bore side of a module containing thousands of fine polymeric hollow fiber membranes. As the mixture travels down the parallel channels, water vapor is drawn through the dense polymeric membrane (while ethanol is rejected) under a driving force established by a vacuum on the shell side of the module.

The membranes are used under rigorous conditions and must have exceptional thermal, mechanical and solvent resistance properties. The membrane is a proprietary formulation based on polyimide (US patent application 2006/0117955) which has been the object of 8 years of development at Laval University and at Vaperma (1,2). This membrane provides high flux and water/ethanol selectivity.

The hollow fiber membranes are assembled into an element which consist of several thousands hollow fibers potted at both ends into a tube sheet. An element is inserted into a stainless-steel pressure vessel to form a module. Modules are arranged in series-parallel in a system.

The key elements of a Siftek™ system are shown in Fig. 2. The vapor feed to the membrane system should be available at a pressure of 6–7 psi gage (142–150 kPa abs) to account for flow control at the inlet,

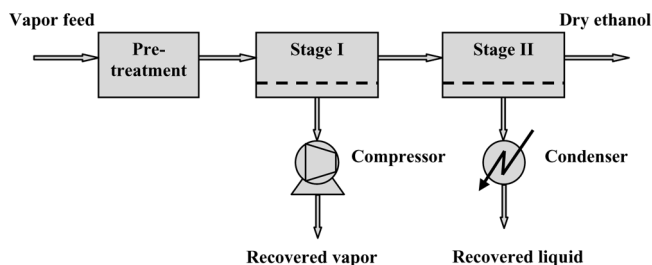


Figure 2. Components for the Siftek™ membrane system.

pressure losses through membrane modules, and the fact that dry ethanol should be produced at a pressure slightly above atmospheric; for vacuum distillation columns, re-compression of the feed may be required. The pretreatment consists of unit operations to remove entrained particles and mist, and heat the ethanol-water vapor mixture to a temperature of about 9°F (5°C) above the dew point. Typically, the operating temperature is between 212–220°F (100–110°C).

A stage is defined by the method used to handle permeate as described below. The number of modules per stage normally decreases as water is withdrawn, to maintain a minimum vapor velocity in the hollow fibers.

The basic options for permeate handling include mechanical vapor recompression (MVR) and condensation as illustrated for Stage I and Stage II in Fig. 2. In both cases, the primary purpose is to establish a driving force for permeation by creating a vacuum on the permeate side of the membrane. A lower vacuum is required for Stage II as the feed water concentration near the product end is less than 1 wt%. Typical values are 10–12 psi vacuum (18–32 kPa abs) for Stage I and 13–14 psi vacuum (5–12 kPa abs) for Stage II. MVR allows to recompress the permeate vapor (mostly water) to the point where it can be reused as heating steam. In a condensation scheme, a vacuum pump is normally used to reach a lower vacuum and to evacuate non-condensable gases.

The degree of dryness of the ethanol product is controlled automatically by varying the power input to the compressors and vacuum pumps part of the system.

Ethanol plants are fully integrated from a mass and energy point of view. There are many options available to recycle the recovered vapor and liquid products to maximize the benefits of a membrane system; they are plant-specific and beyond the scope of this paper. However, it is important to emphasize that the ethanol contents of the permeate(s) is not lost but recovered by recycling at the appropriate point in the process (depending on phase and concentration).

Energy Consumption for Fuel-Ethanol Production

The process flow diagram for a most common dry-milling ethanol plant is presented in Fig. 3 and consists of the following typical steps. The corn kernels are ground into flour; water and enzymes are added, and the slurry is cooked to break down the starch and promote the formation of glucose. This mixture is transferred to fermenters where the yeast converts the sugars into ethanol. The beer, which contains about 10 wt% ethanol and a high concentration of suspended solids, is directed to

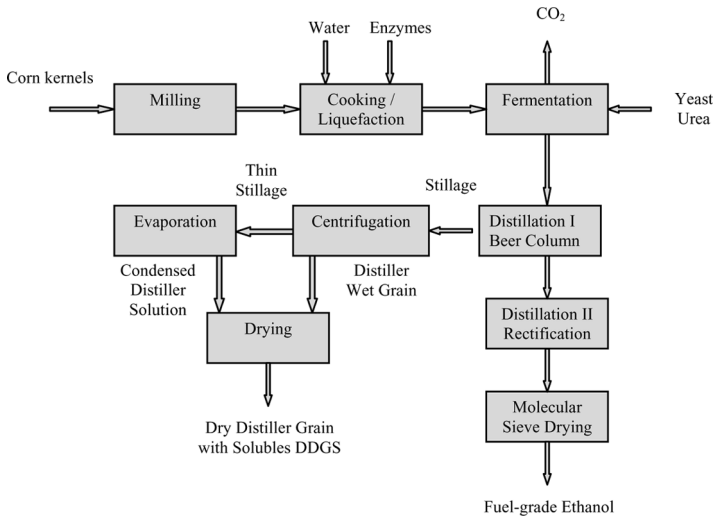


Figure 3. Conceptual process flow diagram for a corn-based, dry-milling ethanol plant.

distillation which is carried out in two steps. In the first step, called the beer column, the stillage (the solids and a large fraction of the water) is collected at the bottom. A water-ethanol mixture containing 40 to 70 wt% ethanol flows to a second column, called the rectification column, where the alcohol contents is increased to the maximum that can be reached by conventional distillation, 90–95 wt% (the azeotrope is 95.6 wt%). Final drying to fuel-grade ethanol is done with molecular sieves.

The stillage is centrifuged to produce distiller wet grain. The liquid fraction is concentrated by evaporation to produce condensed distiller solution which is mixed with the distiller wet grain to produce dry distiller grain with solubles (DDGS).

The total energy used in this process, including natural gas and electricity for non-denatured alcohol, varies between 38,900 and 50,000 BTU/gal (10.8–13.9 MJ/L), the lower figure representing the best available conventional technologies according to Kim and Dale (2005). The distillation and molecular sieve processes described above account for the largest fraction of energy used in a dry-milling plant, as shown in Table 1. Applying an average fraction of 50% from Table 1 to the total energy figures cited above, the energy needed for distillation/dehydration varies between 19,450 and 25,000 BTU/gal (5.4–6.9 MJ/L).

Table 1. Distribution of energy use in a dry milling ethanol plant

Process	Distribution (%)	
	McAloon et al. (6)	Kim and Dale (4)
Milling	1.0	0.8
Cooking/liquefaction	19	29.6
Fermentation	1.0	3.5
Distillation/dehydration	45	56.5
DDGS recovery	34	9.6
Total	100	100

Based on these data, and recognizing that further improvements can be expected from conventional processes (7), the values shown in Table 2 have been selected as reference for the estimation of the potential energy savings obtainable using the Siftek™ technology. These values bracket the range of energy for distillation/dehydration given above and therefore will be used to determine the minimum and maximum energy savings that the proposed technology can provide.

RESULTS AND DISCUSSION

Integration of Siftek™ into Ethanol Plants

Two case studies for New and Retrofit Plants were developed to illustrate the energy savings that can be derived from integration of the Siftek™ technology into ethanol plants. For both cases, the total capacity is 42 Mgal/y (160 ML/y). The full mass and energy balance were done

Table 2. Baseline energy for conventional ethanol distillation/dehydration (this work)

Technology	Total energy for distillation/ dehydration	
	BTU/gal	MJ/L
Best available technology in a modern plant (New plant)	17,942	5.00
Older conventional technology in a existing plant (Retrofit plant)	25,632	7.15

New Plants		Conventional Technology	Siftek™ Drying System	Siftek™ Dewatering System
		↓	Distillation I Beer column	Distillation I Beer column
		↓	Distillation II Rectification column	Distillation II Rectification column
		↓	↓	Siftek™ Membranes I
		Molecular Sieves	Siftek™ Membranes	Siftek™ Membranes II
		↓	↓	↓
Steam/ Compression Energy	BTU/gal kJ/L	17,942 / 0 5,006 / 0	17,248 / 14.8 4,812 / 4.1	7,923 / 1652 2,211 / 461
Total Energy Cost	US\$/gal	16.13	15.52	9.16
	US\$/L	4.26	4.10	2.42
Savings			3.8%	43%

Figure 4. Integration of Siftek™ systems in New Plants.

using HYSIM (Version 2.5) simulation software. Vaperma's proprietary model was used to design the membrane system. Scenarios were developed assuming the following ethanol concentrations: beer = 10 wt%; beer column outlet = 53 wt%; rectification column outlet = 90 wt%. A typical distillation column was simulated with 25 plates, and reflux ratios of 4.1 (beer column) and 1.1 (rectification column). The design of the distillation column ensured that the overall ethanol recovery was 99.95 wt% (i.e., a loss of 0.05 wt% at the bottom of the beer column). Energy costs were estimated at 8.50\$/GJ for natural gas, and .042 \$/kWh for electricity (electricity costs considered were for running the compressors related to the Siftek™ system, in addition to other uses in the plants).

The results for the New Plants case studies are presented in Fig. 4. When building a new plant, maximum benefits are obtained from integrating membranes at the core of the ethanol plant since the costs of conventional equipment can be avoided. However, for this case, it was assumed that membranes would compete with the efficient modern distillation process, i.e., 17,942 BTU/gal (5.0 MJ/L). Two application scenarios were considered, first using the membranes for drying only (New-Drying) and second using the membranes for dewatering (New-Dewatering).

In the New-Drying scenario, a single stage membrane system is used to replace the molecular sieves with a feed from the rectification column at 90 wt% ethanol. The permeate is condensed and returned to the beer column inlet. The results in Fig. 4 show little energy benefit for this case. The bulk of the energy is consumed by distillation, not by the molecular sieves and the overall energy saving is only 3.8%.

In the New-Dewatering scenario, a two stage membrane system is used to replace both the rectification column and the molecular sieves with a feed from the beer column at 53 wt% ethanol. Permeate from the first stage is recompressed, condensed, and the heat recovered is used to heat the beer column; the low ethanol liquid is recycled to the fermenters. Alternatively, this steam could be used to dry stillage with similar energy benefits. The permeate from the second stage is condensed and returned to the beer column inlet. Figure 4 shows that a significant reduction in steam energy is obtained at a relatively small electrical compression load. When converted into cost, savings of 43% are obtained, equivalent to 7.0 US\$/gal, or 1.8 US\$/L.

The results for the Retrofit Plants case studies are presented in Fig. 5. In a retrofit situation the membrane equipment must be added to existing equipment with the potential benefit of de-bottlenecking the plant and increasing throughput. However, a higher baseline for older conventional distillation technology can be used, i.e., 25,632 BTU/gal (7.15 MJ/L). Two application scenarios were considered, first using the membranes for drying only, Retrofit-Drying, and second using the membranes for dewatering, Retrofit-Dewatering. In both cases, the Siftek™ systems were designed to handle 33% of the plant total flow rate.

In the Retrofit-Drying scenario, a single stage membrane system is used on a 33% side-stream of the rectification column at 90 wt% ethanol. The permeate is condensed and returned to the beer column inlet. As was the case for the New Plants, the results in Fig. 5 show little energy benefit for this case.

In the Retrofit-Dewatering scenario, a two stage membrane system is used to treat a 33% stream from the rectification column with an ethanol concentration of 60 wt% ethanol. The permeate streams are handled

		Retrofit Plants		
		Conventional Technology	Siftek™ Drying System	Siftek™ Dewatering System
Steam /	BTU/gal	25,632 / 0	17,246 / 5.0	17,486 / 412
Compression Energy	kJ/L	7,152 / 0	4,812 / 1.4	4,879 / 115
Total Energy Cost	US\$/gal	25.85	25.17	18.53
	US\$/L	6.82	6.64	4.89
Savings			2.6%	28%

Figure 5. Integration of Siftek™ systems in Retrofit Plants.

similarly to the New case. Figure 5 shows an overall energy savings of 28%, equivalent to 7.3 US\$/gal, or 1.9 US\$/L. It is worth noting that, in this scenario, the total energy consumption has been reduced to the level of the best available technology in a modern plant without membranes (Table 2).

The key reason a membrane can separate an ethanol-water mixture with little energy is that separation takes place based on the selectivity of the membrane, without phase change (as is the case for distillation). In a membrane system, the azeotrope has no influence over performance.

A fundamental difference between membranes and molecular sieves used for water removal is that the productivity of a membrane system *increases* with water concentration, while the productivity of molecular sieves *decreases* with water concentration. This is so because the flux through the membrane is proportional to the water concentration in the feed while the water holding capacity of a molecular sieve is finite.

The Siftek™ membrane process was designed to maximize energy savings by using membranes for both dewatering for partial replacement of distillation *and* drying, for replacement of molecular sieves.

The Tiverton Field Demonstration

The Siftek™ technology has been demonstrated in the field at the Greenfield Ethanol plant in Tiverton, Ontario, Canada. The vapor feed was a split stream from the rectification column with an ethanol concentration varying between 75 and 90 wt%. The unit, with a capacity of 1200 kg/day (2600 lbs/day) of vapor feed is fully automated, and operates at a total feed pressure of 3 to 6 psi gage (122 to 142 kPa) and temperature of 105 to 115°C to produce fuel-grade ethanol (>99 wt%).

Figure 6 illustrates the key elements of the field unit. The vaporous feed goes through a knock pot to remove any entrained particles or liquid

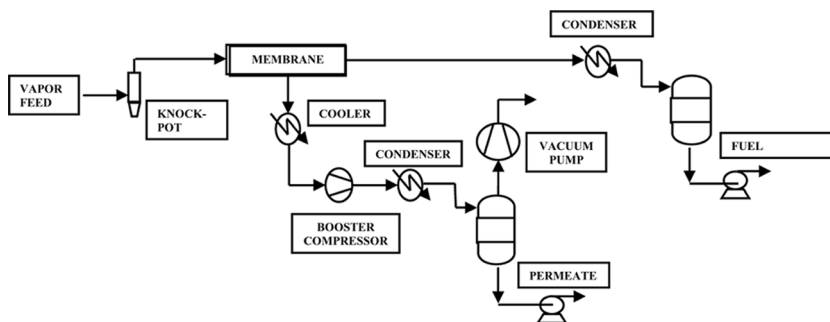


Figure 6. Process flow diagrams for the Siftek™ Tiverton field unit.

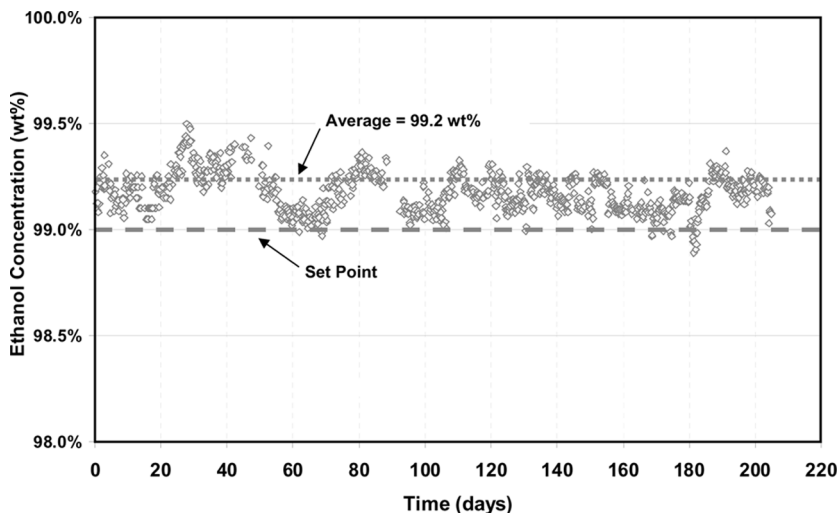


Figure 7. Results for the Siftek™ Tiverton field unit.

droplets and flows to the Siftek™ membrane module. In a single-pass and continuous operation, the ethanol gets concentrated to the set-point value of 99.3 wt% in a single stage membrane system. The vapor product is condensed, flows through a sampling reservoir, and the liquid product is extracted by a pump.

To provide for a wide range of testing conditions, the equipment on the permeate side of the membrane in the field unit is more complex than in a typical plant. The permeate vapor can be cooled and recompressed before being condensed. A vacuum pump maintains the pressure required to achieve the target product quality and extract any non-condensable gases. The condensed permeate flows through a reservoir where the ethanol concentration is measured continuously.

The results of the field demonstration over a period of 200 days are shown in Fig. 7. The unit met the product target consistently with >99% uptime.

CONCLUSIONS

Ethanol is booming, driven by policies to reduce dependency on foreign oil and the production of greenhouse gases. Ethanol producers cannot control the cost of raw materials, but they can reduce the processing cost with innovating technologies.

After corn, the largest cost in the production of ethanol is energy and the largest amount of energy is consumed to purify the ethanol by distillation.

Siftek™ is a polymeric membrane that can be used to dry ethanol in the vapor phase. The membrane preferentially permeates water over ethanol in a continuous process. Energy reductions were obtained because this membrane is well suited to preferentially remove large quantities of water from a 53% ethanol feed.

Siftek™ can be used for new plants or retrofits. In a typical New Plant, the technology can reduce the distillation/dehydration energy by 43% as compared to the currently best available technology (equivalent to 7.0 US\$/gal, or 1.8 US\$/L). In a retrofit situation, Siftek™ can de-bottleneck the plant, increasing capacity while reducing energy.

For a large ethanol plant (42 million gal (160,000 ML) per year), the energy reduction obtained with the Siftek™ technology translates into a reduction of greenhouse gases (GHG) of 21,000 t/year, which is equivalent to over 2 million gallons of gasoline.

The pay-back for the Siftek™ technology is estimated to be less than 1 year for a new plant and between 1 and 2 years for a retrofit plant, based on the energy costs assumed in this paper.

The technology has been demonstrated in the field at the Greenfield Ethanol plant in Tiverton, Ontario, Canada.

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