NET ENERGY ANALYSIS OF ETHANOL PRODUCTION

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INTRODUCTION

In 1972 the Nebraska Agricultural Products Industrial Utilization Committee began a joint program with the Department of Chemical Engineering at the University of Nebraska and the Department of Roads to investigate the suitability of anhydrous ethanol produced by grain fermentation as an automotive fuel additive. Other aspects of this program have been reported previously (4,5). In the overall evaluation of the use of grain alcohol in automotive fuel one should consider the net energy production or consumption associated with the grain alcohol manufacture. As part of a National Science Foundation grant (2) the authors carried out detailed material and energy balances and prepared process designs for a fermentation alcohol plant capable of producing 20 million gallons per year of anhydrous ethanol from corn. A detailed set of utility requirements (steam, electricity, cooling water) for the plant were obtained as a part of this design. This information coupled with Pimentel's analysis (3) of the energy requirements for corn production has made it possible to carry out a detailed total energy analysis for the manufacture of ethanol by the fermentation of corn.

FERMENTATION PLANT

Figure 1 is a block flow diagram of a typical process for producing anhydrous ethanol from corn. Corn is fed from storage to a grinder or hammermill where the particle size is reduced and the interior portions of the grain kernel are exposed. Water is added to the ground corn and the mixture is cooked to solubilize and gelatinize the starch present in the grain. After cooking, amylase, an enzyme, is added to the cooked grain to convert the starch to sugar. The amylase is obtained from fungi propagated on a small portion of the corn. The cooked mixture is placed in fermentation vessels and yeast which has also been propagated within the plant is added. The mixture is allowed to ferment anaerobically for 40 to 45 hours, producing a beer containing 10% alcohol.

This beer is fed to a distillation column and an alcohol-water solution containing 50 to 55% ethanol is produced overhead. The alcohol solution is then sent to a distillation section where the ethanol is concentrated to a 95% solution and undesired materials (aldehydes, fusel oil) are rejected. The alcohol solution is fed to an extractive distillation section where anhydrous ethanol is produced with the aid of benzene. In this analysis a simplified distillation column arrangement has been used to produce ethanol of a purity suitable for use as a fuel additive. A more complex distillation arrangement with a higher steam requirement would be used if beverage grade grain alcohol were being produced.

Bottoms from the beer still contain the non-volatile and non-soluble components from the fermentation section. This material, known as stillage, is centrifuged and the liquid portion sent to multiple effect evaporators where the dissolved solids concentration is increased to approximately 50%. The cake from the centrifuge is combined with the concentrated liquid solution and dried in a fluidized dryer and conveyer to produce distiller's dried grains plus solubles which is sold as cattle feed. It is a high protein material and is a potential source for recovery of a high purity protein concentrate suitable for human consumption (2,5,6).

Table I contains the utility requirements (2) for a plant to produce 20 million gallons per year of anhydrous ethanol from 7.71 million bushels per year of corn (15.5% moisture, 56 lbs/bu). For convenience they have been expressed per bushel of corn and per gallon of ethanol. These utility requirements have been reduced to a total fuel and fresh water requirement according to the arrangement shown in Figure 2. Thus electric power generation requires fresh water and fuel while the cooling tower requires fresh water for make-up and electricity. The steam plant requires fuel, make-up water and electric power. Using the values indicated in Figure 2, it is possible to reduce the entire utility requirement to a fuel and water demand.

Table II contains the equivalent energy requirement for each section of the fermentation ethanol plant as calculated from Figure 2. Values are presented in terms of both Btu's consumed per gallon of ethanol produced and Btu's consumed per bushel of corn fed to the plant. For the alcohol producing portion of the plant the equivalent energy requirement is 107,920 Btu's per gallon of ethanol produced. The portion of the plant associated with the by-product grain production consumes 63,220 Btu's per gallon of ethanol produced. Energy content of products produced in the plant is also contained in Table II. The values reported for chemical products are lower heating values since it is felt that this is a more realistic representation of the actual energy produced in using such materials as fuel. For the distiller's by-product grains, the digestible energy is reported. It is felt that this figure is more consistent with the use of this product as a cattle feed than is the lower heating value.

As dictated by the second law of thermodynamics, the net energy production (energy produced minus energy consumed) in the plant is negative. However, the complete evaluation of the net energy production associated with grain alcohol production requires that we also carry out an analysis of the energy associated with the farming operation in which the corn is produced.

FARMING OPERATION

Pimentel et. al. (3) have made a careful analysis of the energy consumption in 1970 for planting, growing, drying and transporting corn to market. In making this analysis they have in effect gone back to the petroleum products and petrochemicals used in farming and the energy contained in the seed corn. We have modified their values to reflect the use of lower heating values in order to be consistent with the evaluation of the fermentation alcohol plant. The energy required to construct and repair tractors, trucks and other farm machinery was excluded since comparable figures for the construction and repair of process equipment in the alcohol plant were not included.

Table III contains the energy values for the farming operation in

Btu's per gallon of ethanol produced and Btu's per bushel of corn fed to the alcohol plant. The total farming operation consumes 45,986 Btu's per gallon of ethanol produced. Also included in this table are the energy values for the corn produced and for the stalks, cobs and husks. The digestible energy of the corn is reported because it is felt that the alternate utilization of the corn would be as cattle feed. The lower heating value of the cobs, stalks and husks, has been estimated from information published by Miller (1).

Thus for the farming operation it appears that the energy production is over six times as great as the energy consumption. Of course, this is not in violation of the laws of thermodynamics, since the excess energy has come from the sun and been converted to plant material through photosynthesis. The efficiency of photosynthesis has been calculated from the solar energy flux and the energy figures reported here and found to be approximately 0.9%, a reasonable figure.

NET ENERGY ANALYSIS

Table IV contains the overall energy balance for the farming and grain alcohol production operations. The total energy production from ethanol, aldehydes, fusel oil, corn stalks, cobs and husks is 242,494 Btu's per gallon of ethanol produced, while the energy consumption in the farming operation, alcohol plant, and the transportation of stalks cobs and husks to the plant site is 155,466 Btu's per gallon of ethanol produced. The net energy production is the difference in these two values or 87,028 Btu's per gallon of ethanol produced.

The processing associated with the production of distiller's dried grains and solubles is not included in the above energy analysis since it is not directly related to the production of ethanol, but is rather a by-product recovery operation carried out for economic reasons. The net energy loss associated with the by-product grain production is 18,170 Btu's per gallon of ethanol as shown in Table IV.

The energy value of the corn stalks, cobs and husks contained in Table IV is for the total production of these components. Actually, it would be practical and desirable to collect about 75% of this material leaving the remainder in the field for purposes of soil conditioning. If this were done and again if the net energy deficit of the by-product feed production is not included in the analysis then the net energy production is 45,575 Btu's per gallon of ethanol (118,210 Btu's per bushel of corn). If the energy deficit for the by-product production is included in the analysis there is still a net energy production of 27,405 Btu's per gallon of ethanol (71,090 Btu's per bushel of corn) which is approximately 36% of the lower heating value of a gallon of anhydrous ethanol.

CONCLUSIONS

From an analysis of the energy requirements associated with the production of corn in an average farming operation and the energy requirements necessary to convert this corn to anhydrous grain alcohol it appears that if 75% of the stalks, cobs and husks are used as an energy source that there will be a net energy production of at least 27,405 Btu's per gallon of ethanol produced. If the energy consumption associated with the preparation of distiller's by-product grains is not included (since it is not a necessary part of the grain alcohol production) then the overall net energy production is at least 45,575 Btu's per gallon of ethanol produced. This ability to have a net energy production associated with the total process is the result of harnessing solar energy through photosynthesis. Thus the potential actually exists to extend our automotive fuel energy supply through the addition of grain alcohol produced by grain fermentation. Ethanol synthesized from hydrocarbons via ethylene, however, must be accompanied by a net energy loss (second law of thermodynamics).

The amount of ethanol that will ultimately find use as an automotive fuel additive will depend on other factors in addition to the net energy production associated with its manufacture. Results of other research work (4,5) indicate that such usage may be desirable and economically practical in the future.

LITERATURE CITED

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Table I
Utility Consumption for
the Production of Ethanol by
the Fermentation of Corn

Alcohol Plant	Per Bu. Corn	Per Gal.EtOH
Steam (50 psig), lb.	118.2	45.6
" (15 psig), lb.	75.6	29.2
Cooling Water (25°F Rise), Gal	43.6	16.8
Electric Power, Kw-Hr.	5.46×10^{-1}	2.10×10^{-1}
Benzene, lb.	3.11×10^{-3}	1.20×10^{-3}
By-Product Cattle Feed		
Steam (50 psig, lb.	85.7	33.0
Cooling Water (25°F Rise), Gal	286.4	110.4
Electric Power, Kw-Hr	2.54×10^{-1}	9.80×10^{-2}
Coal (10,000 Btu/lb), lb.	4.86	1.87

Manpower - 5 shift positions plus 5 unclassified personnel

Table II
Energy Consumption and Production
In the Manufacture of Ethanol by
the Fermentation of Corn

Energy Consumption In a Fermentation Ethanol Plant

Plant Section	Btu/Bu.Corn	Btu/Gal.EtOH
Liquid Concentration	113,120	43,610
By-product Grain Drying	50,860	19,610
Subtotal, By-products	163,980	63,220
Grinding, Cooking, Propagation	62,680	24,160
Fermentation	1,460	560
Beer Still and Centrifuge	104,830	40,420
Distillation	74,100	28,560
Dehydration	36,890	14,220
Subtotal, Ethanol	279,960	107,920

Energy Content of Products From a Fermentation Ethanol Plant

Item	Btu/Bu.Corn	Btu/Gal.EtOH
Ethanol, 1)	196,108	75,600
Aldehydes, Fusel Oil, 1)	2,802	1,080
By-product Grains, 2)	116,860	45,050
	315,770	121,730

1) Lower heating value. 2) Digestible energy.

Table III
Energy Consumption and Production in Corn Farming

Energy Consumption in Corn Farming

Item	Btu/Bu. Corn	Btu/Gal.EtOH
Seed Corn	2,915	1,124
Fertilizer	51,700	19,930
Herbicide & Insecticide	1,077	415
Gasoline	37,231	14,353
Electricity	15,178	5,851
Irrigation	1,645	634
Labor	240	93
Drying	5,876	2,265
Transportation of Corn	3,427	1,321
Total	119,289	45,986

Energy Content of Products From Corn Farming

Item	Btu/Bu.Corn	Btu/Gal. EtOH
Corn, 1)	341,750	121,740
Stalks, Cobs, Husks, 2)	430,127	165,814
Total	771,877	297,554

1) Digestible energy. 2) Lower heating value.

Table IV
Overall Energy Balance For Grain Alcohol Production From Corn

Energy Production	Btu/Bu.Corn	Btu/Gal.EtOH
Ethanol	196,109	75,600
Aldehydes, Fusel Oil	2,802	1,080
Stalks, Cobs, Husks	430,127	165,814
Total	629,038	242,494
Energy Consumption		
Farming Operation	119,289	45,986
Transportation of stalks, etc.	4,047	1,560
Alcohol Plant	279,960	107,920
Total	403,296	155,466
Net Energy Production	225,742	87,028
Net Energy Loss		
By-product Grain Production	47,120	18,170

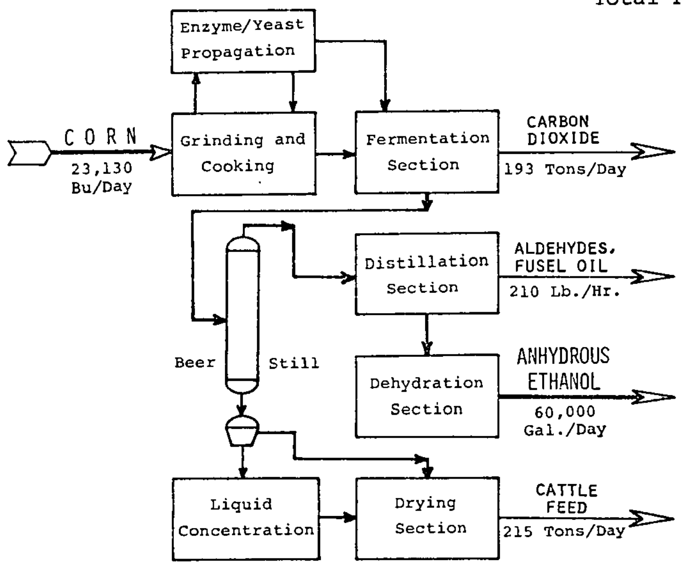

Figure 1 - Process Block Flow Diagram for a Fermentation Ethanol Plant.

$$\text{Total Power } P_T \text{ (kw)} = 1.05(P_o + .00105S_o + .0706CW_o)$$
$$\text{Total Fuel (Btu/Hr)} = 10{,}000P_T + 1.32S_o\Delta H$$

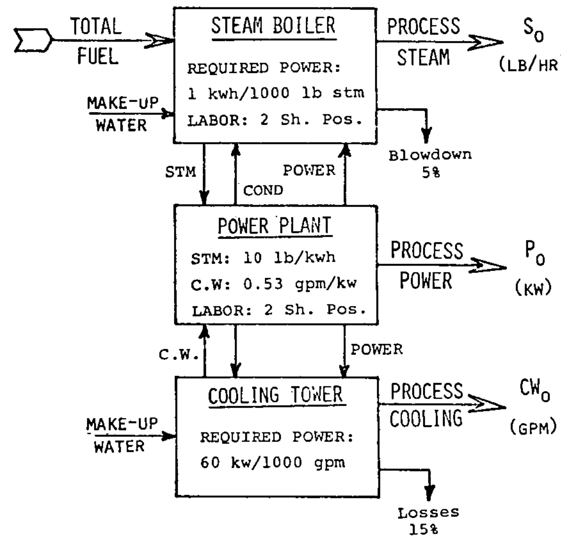

Figure 2 - Block Flow Diagram for the Utility - Fuel Relationship.