



## REDUCTION OF STEAM AND COOLING WATER CONSUMPTION IN FUEL ALCOHOL DISTILLATION COLUMNS

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### **Abstract**

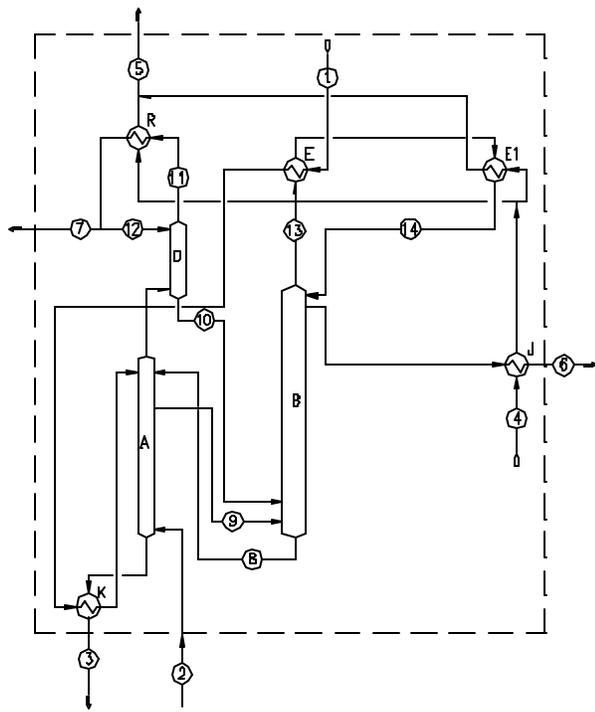
*This publication describes the availability (or exergy) analysis of a cane sugar fuel alcohol distillery, for energy optimisation. In a fuel alcohol distillery, the aim is to separate the ethanol from wine, within the specified purity, with the minimum possible energy input. Operating data are used in energy (including availability) and economic audits. The coefficients in a mathematical simulation of the process were adjusted to reproduce real column performance. The adjusted program was used to analyse the effect of mechanical compression of ethanol vapour on steam and cooling water consumption and on availability and effectiveness for two different options.*

**Key words:** Fuel alcohol, distillation, availability, exergy, rational energy use.

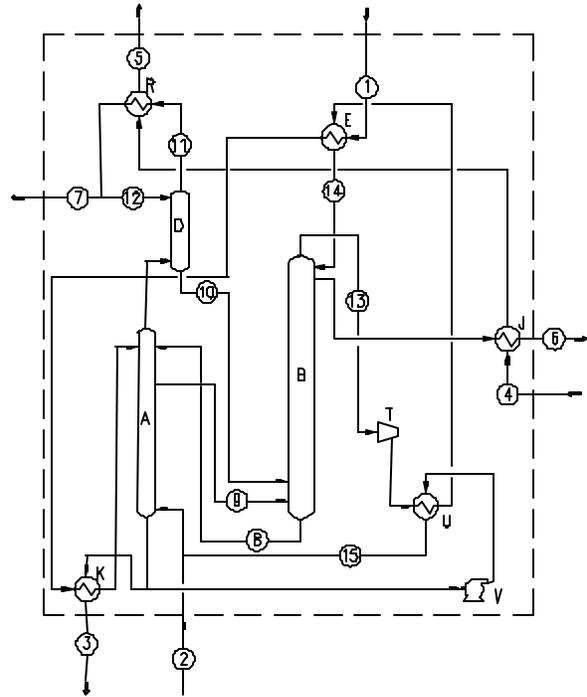
### **1. INTRODUCTION**

Distillation is the physical separation of a mixture of liquids whose saturation pressures differ at any given temperature. It accounts for 95% of all liquid mixture separations and about 15% of total energy consumption in chemical industries (Zanetti, 1997). A tray distillation column, common in fuel alcohol distilleries, consists of a vertical series of trays (or plates), containing liquid through which rising vapour flows. The concentration of the more volatile component (ethanol) increases in the rising vapour and decreases in the falling liquid. Vapour leaving the first (top) tray of the column enters the condenser. Part of the condensate is reflux (liquid returned to the column) and the rest distillate (product). The liquid leaving the lowest tray of the column is removed as bottoms product (Coulson & Richardson 1976, Perry, R.H. and Chilton 1980, IPT 1990).

During several years, the (selling) price of fuel alcohol was attractive and stable, so rational use of the bagasse (residue) for energy or other byproducts could be neglected. Over the past few years, however, fuel alcohol prices have been unstable, while bagasse sub-products such as electricity and charcoal (especially if activated) are economically more attractive. Furthermore, the use of river water for cooling is being charged, so interest in alternative technologies is growing. Several investigations have been published on the use of vapor recompression and heat pumps to reduce the use of condenser cooling water (Annakou & Mizsey, 1995. NULL, 1976; MIX, DWECK & WEINBERG, 1978; Björn, Grén & Ström, 1991). It is proposed to compare the simulated energy and economic performance of recompression schemes with the standard scheme (direct steam injection).



**Fig. 1.** Flow diagram of Process I



**Fig. 2.** Flow diagram of Process II

Three alternative processes for a distillation apparatus with a capacity of 90.000 m<sup>3</sup> of hydrous alcohol a day are compared in a mathematical computer simulation on the basis of energy and availability balances. In Process I, the theoretical number of trays is adjusted to reproduce the performance of a real distillation process. In Process II, the condensation enthalpy of compressed product ethanol vapour evaporates steam from the spent liquor to energise the column. In Process III only part (55%) of the alcohol vapour is recompressed, the remainder being condensed.

## 2. PROCESS DESCRIPTIONS

Fig. 1 describes the simulation model of Process I. The control volume is bounded by the dashed line. Vapour leaving the top of column D is condensed in a single condenser while vapour from the top of column B passes through two condensers. Equipment are identified by letters and streams by numbers. The equipment are: A (distillation column) with 24 trays, D (head concentration column), K (heat recuperator), R (condenser), B (rectifying column) with 49 trays, E (pre-heater), E1 (condenser), J (cooler). And the flows are: 1 (wine), 2 (vapour), 3 (spent liquor), 4 (cooling water in the entrance), 5 (cooling water in the exit), 6 (hydrous alcohol), 7 (secondary alcohol), 8 (phlegma), 9 (phlegm), 10 (bottoms in D), 11 (top stream in D), 12 (reflux in D), 13 (top stream in B), 14 (reflux in B). Inputs to the process are: 2,58 kg of steam and 62,7 kg of cooling water per kg of hydrous alcohol produced.

Fig.2 is the flow diagram for Process II. Stream 13 from column B, is compressed in T, then condensed in U, pre-heats wine in E and returns to B as reflux (stream 14). Part of the spent liquor, stream 15, is pumped in V and evaporated in U by heat from stream 13. Stream 15 from U is mixed with steam injected at the base of column A. The power of pump V is 20.25 W and of compressor T 382.5 kW. Results are described in Tables 2 and 3.

Process III is similar to Process II but only 55% of the ethanol vapor is recompressed. The remainder (45%) is condensed by the cooling water, returning to the column as reflux, as in Process I (Silveira 2000).

### Equations used

The laws of thermodynamics (Kotas 1985, Moran & Shapiro 1996, Hatsopoulos & Keenan 1993, Faria 1986) are used to analyse and evaluate the processes.

### Enthalpy

$$H_k = M_k \cdot [(h_k - h_{ok}) + (X_k \cdot LCV_E)] \quad (1)$$

where:  $M_k$  = mass flow of the "kth" stream (kg/h)  
 $h_k$  = specific enthalpy of the "kth" stream (kJ/kg)  
 $X_k$  = alcohol strength INPM of the "kth" stream.  
 $LCV_E$  = lower calorific value of ethanol (26.80 MJ/kg).  
subscript "o" indicates standard state:  $T_o = 298.15$  K and  $p_o = 101.32$  kPa  
subscript "k" indicates stream "k"

### Entropy

$$S_k = [X_{mk} \cdot c_{pomet} + (1 - X_{mk}) \cdot c_{pomag}] \cdot \ln \left( \frac{T_k}{T_o} \right) \cdot n_k + \Delta S_{mistK} \quad (2)$$

$$\text{and } \Delta S_{mistk} = -n_k \cdot R_m \cdot (X_{mk} \cdot \ln(X_{mk}) + (1 - X_{mk}) \cdot \ln(1 - X_{mk})) \quad (3)$$

where:  $c_{pomet}$  = molar specific heat at constant pressure of ethanol at  $T_o$  (113.498 kJ/kmol.K).  
 $c_{pomag}$  = molar specific heat at constant pressure of the water at  $T_o$ , (75.306 kJ/kmol.K).  
 $T_k$  = temperature of stream "k" (K).  
 $n_k$  = total molar flow rate of stream "k" (kmol/h).  
 $R_m$  = constant universal of the gases, to the base molar (8.315 kJ/kmol.K)  
 $X_{mk}$  = alcoholic graduation of stream "k" on a molar basis.

### The First Law of Thermodynamics (neglecting kinetic and potential energies):

$$H_{sai} - H_{ent} = Q - W_t \quad (6)$$

where:  $H_{sai}$  = summation of enthalpy transfer rates (in relation to  $T_o$ ) for the exit streams (kW)  
 $H_{ent}$  = summation of enthalpy transfer rates (in relation to  $T_o$ ) for the inlet streams (kW)  
 $Q$  = net heat transfer to the system from the environment (kW).  
 $W_t$  = net power input to the system (kW).

### The Second Law of the Thermodynamics, neglecting kinetic and potential energies:

Availability (rate) of stream "k",

$$\Lambda_k = H_k - T_o \cdot S_k \quad (7)$$

Process Effectiveness,

$$\xi_p = \frac{\Lambda_{out}}{\Lambda_{in} + W_t} = (\text{output availability}) / (\text{input availability}) \quad (8)$$

where:  $\Lambda_{out}$  = availability (rate) summation for the exit streams (kW).  
 $\Lambda_{in}$  = availability (rate) summation for the input streams (kW).

Irreversibility,

$$I = \Lambda_{in} + W_t - \Lambda_{out} \quad (9)$$

$$\text{Effectiveness of the equipment (group)} \quad \xi_a = \frac{\ddot{E}_{ah} + \ddot{E}_{a2} - \ddot{E}_{vin}}{\ddot{E}_{st} + W_t} \quad (10)$$

where: the numerator of the right hand term represents reversible work of separation (neglecting the availability of the spent liquor, which is wasted)

the denominator represents reversible work used to accomplish the real process.

$\Lambda_{ah}$  = availability of the hydrous alcohol stream (kW)

$\Lambda_{a2}$  = availability of the of secondary alcohol stream (kW)

$\Lambda_{vin}$  = availability of the wine stream (kW)

$\Lambda_{st}$  = availability of the steam stream (kW).

### 2.3 Results

In all cases, heat transfer between the control volume and the environment was neglected. Pump efficiency is assumed 42 % for both processes II and III. Alcohol compressor efficiency is taken as 72.5% for Process II and 70% for Process III.

The equipment effectiveness,  $\xi_a$ , was evaluated with the spent liquor at the reference (atmospheric) temperature.

**Table 1.** Results for Process I

	Stream	M (kg/h)	t (C)	X (%)	H (kW)	T <sub>o</sub> S (kW)	$\Lambda$ (kW)
Inlet Streams	Wine	44 763	35	6.61	22 533	700.9	21 832
	Steam	7 683	120	---	5 562	4 378	1 185
	Cooling water	186 752	30	---	1 084	1 070	13.74
	TOTALS	239 198	---	---	29 179	6 149	23 031
Outlet streams	Spent liquor	49 280	94	0.012	4 024	3 574	449.6
	Cooling water	186 752	39.5	---	3 142	3 066	76.87
	Hydrous Alcohol	3 006	35	93.51	20 947	42.1	20 904
	Second. Alcohol	159.9	85	88.90	1 066	8.04	1 058
	TOTALS	239 198	---	---	23 179	6 690	22 488

**Other results:** Total power input  $W_t = 0$  kW  
 Process Effectiveness  $\zeta_p = 96.7\%$   
 Equipment Effectiveness  $\xi_a = 3.9\%$   
 Irreversibility  $I = 768$  kW.  
 Specific steam consumption  $SC_s = 2.5$  kg/dm<sup>3</sup> of hydrated alcohol  
 Cooling water flow  $W_{cw} = 50.0$  dm<sup>3</sup>/dm<sup>3</sup> of hydrated alcohol

**Table 2. Results for Process II**

	Stream	Fluid	M (kg/h)	t (C)	X (%)	H (kW)	T <sub>o</sub> S (kW)	Λ(kW)
Inlet Streams	1	Wine	44 763	35	6.61	22 533	700.8	21 832
	2	Vapour	2 233	120	---	1 617	1 272	344.41
	4	Cooling Water	51 000	30	---	296	292.3	3.75
	TOTALS		97 996	---	---	24 446	2 266	22 180
Outlet streams	3	Spent liq.	43 830	94	0.013	2 025	1 866	159.47
	5	Cooling water	51 000	39.5	---	787.6	769.2	18.42
	6	Hydrous alcohol	3 006	35	93.52	20 949	42.09	20 907
	7	Second. Alcohol	159.9	85	88.90	1 066	8.05	1 058
	TOTALS		97 996	---	---	24 828	2 685	22 143

**Other Results:** Total power input  $W_t = 676$  kW  
 Process Effectiveness  $\zeta_p = 96.6\%$   
 Equipment Effectiveness  $\xi_a = 5.1\%$   
 Irreversibility  $I = 790$  kW.  
 Specific steam consumption  $SC_s = 0.6$  kg/dm<sup>3</sup> of hydrated alcohol  
 Cooling water flow  $W_{cw} = 11.7$  dm<sup>3</sup>/dm<sup>3</sup> of hydrated alcohol

**Table 3. Results for Process III**

	Stream	Fluid	M (kg/h) <sup>1</sup>	t (C) <sup>2</sup>	X (%) <sup>3</sup>	H (kW) <sup>4</sup>	I (kW) <sup>5</sup>	Λ(kW) <sup>6</sup>
Inlet Streams	1	Wine	44 968	35	6.61	22 636	624.6	22 011
	2	Vapour	5 230	125	- o -	3 796	2 906	890.2
	4	Cooling water	76 290	28	- o -	265.7	262.8	2.88
	TOTALS		126 488	-o-	- o -	26 698	3 793.38	22 904
Outlet streams	3	Spent liquor	46 998	93.6	0.01	3 795	3 394	400.80
	5	Cooling water	76 290	37.5	- o -	1 108	1 081.7	26.75
	6	Hydrous alcohol	3 037	35	92.90	21 022	37.49	20 985
	7	Second. Alcohol	163.1	78.6	89.06	1 088	8.06	1 080
	TOTALS		126 488	-o-	- o -	27 013	4 521	22 492

<sup>1</sup>mass flow <sup>2</sup>temperature <sup>3</sup>alcohol strength INPM <sup>4</sup>enthalpy <sup>5</sup>irreversibility <sup>6</sup>availability

**Other Results:** Power consumption  $W = 317$  kW  
 Process Effectiveness  $\zeta_p = 96.8\%$   
 Equipment Effectiveness  $\xi_a = 4.4\%$   
 Irreversibility  $I = 729.2$  kW.  
 Specific steam consumption  $SC_s = 1.39$  kg/dm<sup>3</sup> of hydrated alcohol  
 Cooling water flow  $W_{cw} = 20.4$  dm<sup>3</sup>/dm<sup>3</sup> of hydrated alcohol

#### 4. ECONOMIC CONSIDERATIONS

Although the thermodynamic analysis indicates that the use of the ethanol latent enthalpy could improve the efficacy of the process, an engineering evaluation requires an economic analysis to determine if the modification would be financially rewarding.

Before considering the capital investments required for Processes II and III, a comparative evaluation is required of the operational costs in relation to Process I.

The power required to drive the compressors was costed at R\$47.4/MWh (approximately US\$18.90/MWh) (Carpio, 2000). The cooling water consumption was costed at R\$0.10/m<sup>3</sup>.

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Pump efficiency is assumed 42% for both processes II and III. Alcohol compressor efficiency is taken as 72.5% for Process II and 70% for Process III

### Process II vs Process I

Increase in electricity consumption	= 167.4 kW
Economy in cooling water consumption	= 19.83 m <sup>3</sup> /h
Additional annual expense with electricity	= R\$ 73 884.48
Additional annual operation and maintenance costs	= R\$ 27 087.03
Additional annual insurance costs	= R\$ 13 543.51
Annual economy in water consumption	= R\$ 8 996.53
Annual income tax relief (equivalent economy)	= R\$ 51 969.81
<b>Total (additional) expenses</b>	<b>= R\$ 114 515.02</b>
<b>Total economy</b>	<b>= R\$ 60 966.34</b>

It is seen that even without accounting for the investment (**R\$ 1 354 351.33**) the option is not economically viable.

### Process III vs Process I

Increase in electricity consumption	= 343.6 kW
Economy in cooling water consumption	= 19.83 m <sup>3</sup> /h
Additional annual expense with electricity	= R\$ 35 997.21
Additional annual operation and maintenance costs	= R\$ 16 351.97
Additional annual insurance costs	= R\$ 8 175.98
Annual economy in water consumption	= R\$ 6 147.34
Annual income tax relief (equivalent economy)	= R\$ 28 577.32
<b>Total (additional) expenses</b>	<b>= R\$ 60 525.16</b>
<b>Total economy</b>	<b>= R\$ 34 724.66</b>

Again it is seen that even without the investment (**R\$ 817 598 33**) the option is not economically viable.

## 5. DISCUSSION OF RESULTS

The difference in process viability from economic as compared to availability considerations is explained by the relatively low steam turbine efficiency assumed for electricity generation and electricity costs. Due to the low turbine efficiency, the electricity generated by surplus steam is less than its availability and the total availability spent in Processes II and III is greater than in Process I. Due to the electricity cost, expenses for the extra (makeup) work required for the compressor are greater than the savings in the water consumption costs. The picture could change if water costs

were to increase substantially and much more efficient turbines and compressors were available. For example an increase in compressor efficiency to 90% would reduce annual electricity costs by 22% (about R\$16000.00 and R\$8000.00 for Process III) and a fivefold increase in water charges would increase water savings by about R\$34600.00 for Process II and R\$25000.00 for Process III. The total savings would increase by R\$50000.00 and R\$33000.00 respectively. In this case running costs would nearly break even for Process II and there would be a small net saving for Process III. However the investment would not be recovered even at much higher water charges, due to the relatively high cost of the compressors.

## 6. CONCLUSIONS

Re-boiling the bottoms product of the distillation column by condensing compressed alcohol vapour, can reduce both condenser cooling water and boiler steam mass flows by more than 70%. The reduction in boiler steam requires more high pressure steam, a more efficient turbine, or electricity power supply to drive the turbo-generator. The reversible separation work for Process I would be 130.83 kW and for Process II 133.3 kW. However the reversible work spent to accomplish the process would be 1185 kW in the first case, and 726.9 kW in the second. Hence, according to Eq.(10), the effectiveness of the apparatus would be 3.9 % for the original process (Process I), 5.1 % for Process II and 4.4% for process (Process III). The economic results are even more discouraging. Due to present high equipment costs, even a tenfold increase in water costs would be insufficient to provide a reasonable payback period and recompression is still not economically viable.

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