HEAT RECOVERY FROM MULTIPLE EFFECT EVAPORATOR USING VAPOR RECOMPRESSION

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Abstract. *Multiple Effect Evaporator (MEE) is the equipment that demands the largest thermal energy in the production of sugar and alcohol. However, it is possible the heat recovery through the MEE using the vapor formed during the operation (vegetal vapor) as thermal utility in the remainder of the process. One way to improve this recovery is using the thermocompression or the mechanical recompression, that increase the conditions of temperature and pressure of the vegetal vapor, extending its applicability. In this work the consumption and thermal energy recovery are studied using mechanical recompression of vapor. The demands of the mechanical power in the compressor and the increase of power in the cogeneration cycle are compared. The results show that the recovery depend mainly from which effect of MEE the vapor recompression occurs and despite the latest advances, many resources of improvements can still be applied.*

Keywords*: Multiple Effect Evaporator, Vapor Recompression, Heat Recovery, Cogeneration*

1. INTRODUCTION

Nowadays, beyond sugar and alcohol, Brazilian industries in the sector also commercialize surplus of electrical energy generated in cogeneration cycles installed in their plants. The bagasse proceeding from juice extraction of sugarcane is fired as fuel and provides thermal energy used to the steam generation in high pressure conditions. During the operation for power generation, the steam can be extracted from turbine in medium pressure for supply the heat demand in process. Although, if the steam is not extracted to process, it can used to increase the surplus of electrical energy until to be exhausted in low pressure for condensing operation (Fig. 1). The cogeneration corresponds to the simultaneous production of different forms of useful energy to a determined process unit from the same primary source (Balestieri, 2002). So that, to reduce the thermal energy consumption in the production process of sugar and alcohol is essential to increase the electric energy generation of the industrial plant.

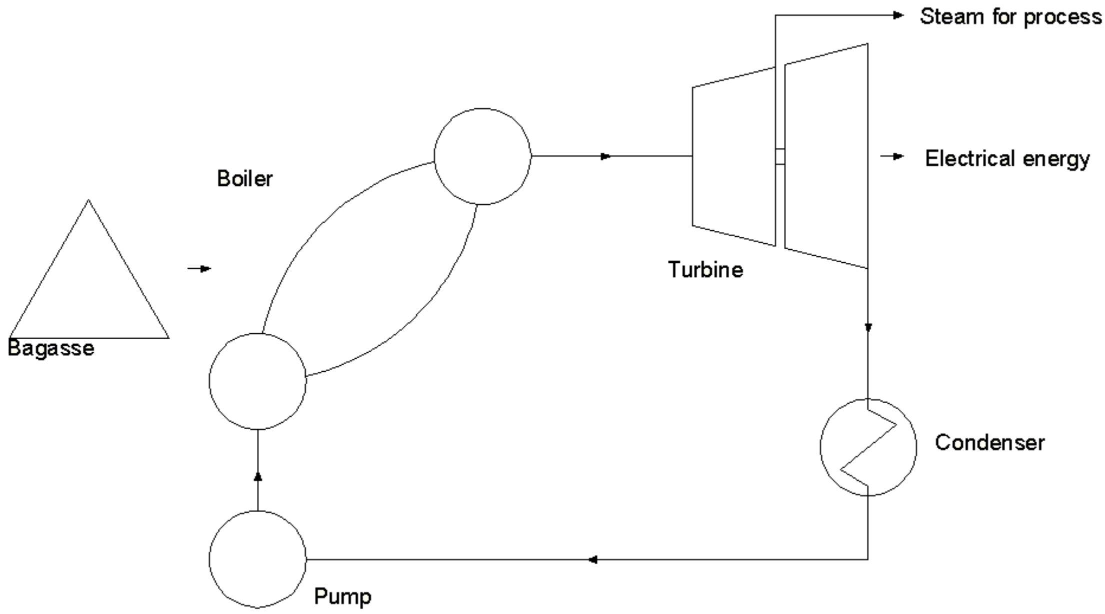

Figure 1. Cogeneration cycle scheme

However the evaporation is a unit operation that demands the major consumption thermal in the sugar and alcohol production process, it also enables a large energy recovery. For that, an efficient evaporation system is fundamental for the adequate thermal balance of the process (Gonzalez, 2005). The evaporation in most Brazilian sugar and alcohol plants occurs in a Multiple Effect Evaporator (MEE), created in 1932 by Norbert Rilieux (Fig. 2). The advantage of this system is the possibility for the vegetal vapor formed during juice concentration from an effect, be used as heat source for juice concentration in the next effect. Only the first effect is fed by steam extracted from the cogeneration cycle. It is possible also make extractions (bleeds) of vegetal vapor between effects to supply others thermal demands of process. This measure reduces the global consumption of process (Higa *et al*, 2009).

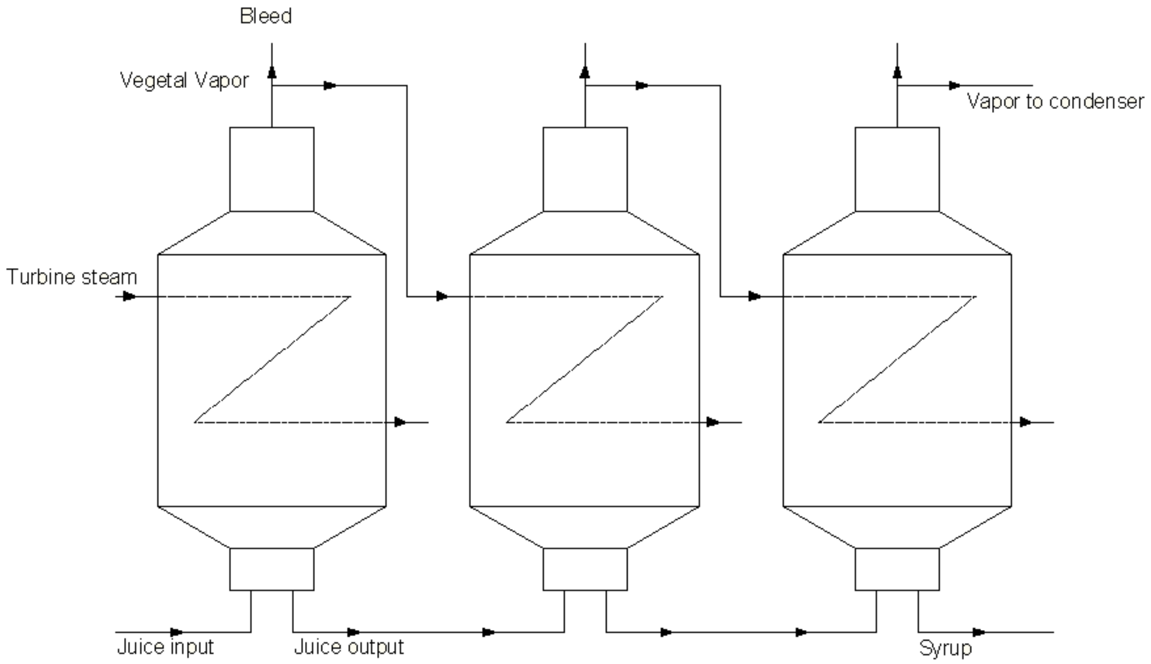

Figure 2. Multiple Effect Evaporator (MEE) scheme

One possibility to decrease still more the thermal consumption of the process is the use of mechanical vegetal vapor recompression. Using this measure, pressure and temperature of vegetal vapor that leaves an effect are increased to levels that enable its use as heating source in previous evaporation effects. Consequently, demand for steam extraction from turbine is reduced for the process. To increase surplus of electrical energy production in cogeneration cycle, systems of extraction-condensing turbines (Fig. 1) or others similar systems may be used. In this case, the saved steam due to the reduction in process consumption (backpressure steam) continues generating power in turbine until be exhausted to condenser (condensation steam) increasing the surplus of electrical energy generation. However, it is important to observe that the mechanical recompression will be advantageous only if the increase of surplus power overcomes the power demands necessary for vegetal vapor recompression.

2. MODEL

The analysis of the optimization model of these systems is based on thermodynamics principles (Blackadder and Nedderman, 2008, Foust, *et al*, 1983), as described in the following section.

2.1. Evaporation in multiple effects

Figure 3 shows the scheme of a single effect from a multiple effect evaporator (MEE).

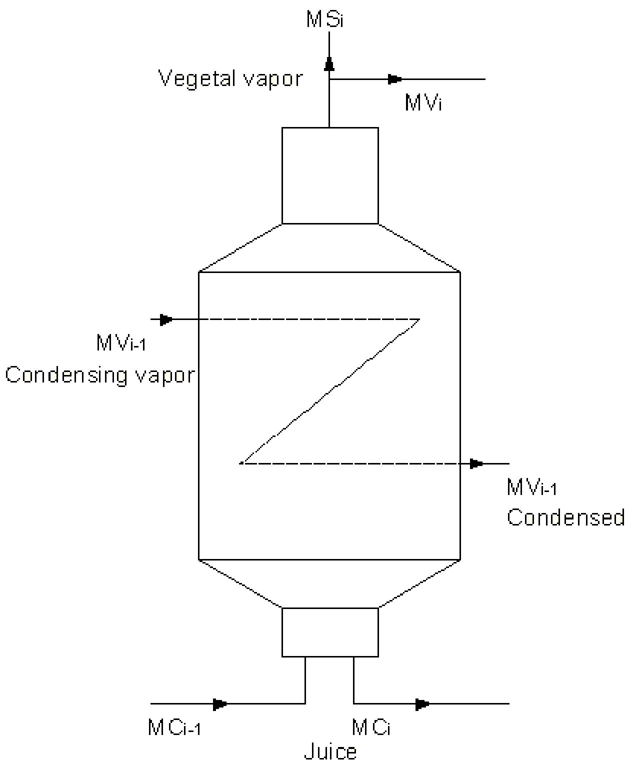

Figure 3. Single effect scheme

Based on the model is considered: juice enters in the effect at same enthalpy of the previous effect and exits more concentrated at the same temperature of this effect; vegetal vapor comes out at same temperature of this effect; and condensing vapor enters as saturated vapor at same temperature of previous effect and exits as saturated liquid at the same temperature of this effect. For the mass and energy balances are not considered boiling-point elevation, which occurs on juice due to solids concentration and pressure of liquid column in the evaporator. From this simplification the equations result in linear model. Based on scheme of the Fig. 2, the mass and energy balances may be calculated from Eq. (1) and Eq. (2), respectively:

$$MV_i + MS_i = MC_{i-1} - MC_i \tag{1}$$

$$MV_{i-1}\, hV_{i-1} + MC_{i-1}\, hC_{i-1} = (MV_i + MS_i)\, hV_i + MC_i hC_i + MV_{i-1}\, hL_{i-1} \tag{2}$$

Where:

- i : index of the effect;
- MV_i : mass flow of vegetal vapor used in the effect $i+1$ [kg/s];
- MV_{i-1} : mass flow of condensing vapor [kg/s];
- MS_i : mass flow of vegetal vapor extracted to the process [kg/s];
- MC_i : mass flow of juice at the exit in [kg/s];
- MC_{i-1}: mass flow of juice at the inlet [kg/s];
- hV_i : specific enthalpy of vegetal vapor generated in the effect [kJ/kg];
- hV_{i-1}: specific enthalpy of condensing vapor [kJ/kg];
- hL_{i-1} : specific enthalpy of condensed [kJ/kg];
- hC_i : specific enthalpy of juice at the exit [kJ/kg];
- hC_{i-1} : specific enthalpy of juice at the inlet [kJ/kg];

In the first effect, the mass flow of condensing vapor is the mass flow of the steam extracted from the turbine and consumed in the evaporator (MV_{ve}). Vapor enthalpies are determined by tables of water vapor and juice enthalpies are calculated by specific heat of sugarcane juice using Eq. (3) and Eq. (4), according to Hugot (1977), Payne (1989) and Camargo (1990).

$$hC_i = cp_i T_i \tag{3}$$

$$cp_i = 4{,}187\left(1-0{,}006Bx_i\right) = 4{,}187\left(1-0{,}006\frac{MC_0}{MC_i}Bx_0\right) = 4{,}187\left(1-\frac{csol}{MC_i}\right) \tag{4}$$

Where:

- cp_i : specific heat of the sugarcane juice at the exit of the effect [kJ/kg°C];
- T_i : temperature of the juice [^{o} C];
- Bx_i : concentration in mass of solids in the juice [Brix];
- $csol$: constant to calculate specific heat;

If the previous equations are combined, results in Eq. (5), which can be applied for each effect.

$$\left(MC_{i-2}-MC_{i-1}-MS_{i-1}\right)\left(hV_{i-1}-hL_{i-1}\right)+MC_i\left(hV_i-4{,}187T_i\right)=MC_{i-1}\left(hV_i-4{,}187T_{i-1}\right)+4{,}187csol\left(T_{i-1}-T_i\right) \tag{5}$$

Considering a 5 effects evaporator, results in the following system of the Eq. (6).

$$\begin{cases} MV_{ve}\left(hV_{ve}-hL_{ve}\right)+MC_1\left(hV_1-4{,}187T_1\right)=MC_0\left(hV_1-4{,}187T_0\right)+4{,}187csol\left(T_0-T_1\right) \\ \left(MC_0-MC_1-MS_1\right)\left(hV_1-hL_1\right)+MC_2\left(hV_2-4{,}187T_2\right)=MC_1\left(hV_2-4{,}187T_1\right)+4{,}187csol\left(T_1-T_2\right) \\ \left(MC_1-MC_2-MS_2\right)\left(hV_2-hL_2\right)+MC_3\left(hV_3-4{,}187T_3\right)=MC_2\left(hV_3-4{,}187T_2\right)+4{,}187csol\left(T_2-T_3\right) \\ \left(MC_3-MC_3-MS_3\right)\left(hV_3-hL_3\right)+MC_4\left(hV_4-4{,}187T_4\right)=MC_3\left(hV_4-4{,}187T_3\right)+4{,}187csol\left(T_3-T_4\right) \\ \left(MC_3-MC_4-MS_4\right)\left(hV_4-hL_4\right)+MC_5\left(hV_5-4{,}187T_5\right)=MC_4\left(hV_5-4{,}187T_4\right)+4{,}187csol\left(T_4-T_5\right) \end{cases} \tag{6}$$

2.1. Mechanical recompression

On systems using mechanical recompression, a part of vegetal vapor formed in an effect i (MV_{rec}) is compressed until the pressure of an effect j where is used as condensing vapor. However, vapor gets high temperatures of superheated after recompression. Therefore, before going into effect j, recompressed vapor must be cooled in a desuperheater in order to assure a better temperature condition to evaporate the juice. Desuperheater may use part of condensed liquid from the same effect j (ML_{cd}) to reduce the vapor temperature until saturation or close to the saturation state, forming the vapor (MV_{vd}) (Fig.4).

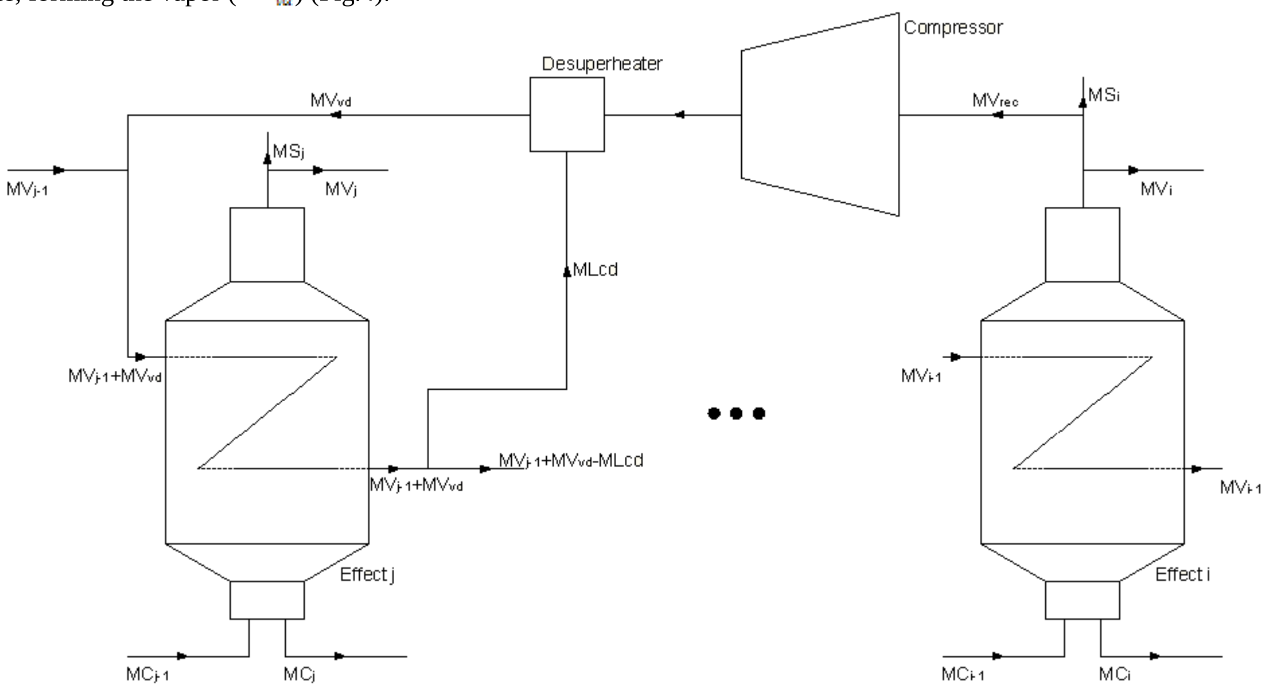

Figure 4. Scheme of mechanical recompression system

Considering the mechanical recompression, the mass balance for the effect i can be rewritten as Eq. (7). Consequently the energy balance for the effect $i+1$ is given by Eq. (8), and the energy balance for the effect j by Eq. (9). Moreover, the mass balance and energy balances for the desuperheater result in the Eq. (10) and Eq. (11), respectively.

$$MV_i = MC_{i-1} - MC_i - MS_i - MV_{rec} \tag{7}$$

$$\left(MC_{i-1} - MC_i - MS_i - MV_{rec}\right)\left(hV_i - hL_i\right) + MC_{i+1}\left(hV_{i+1} - 4{,}187T_{i+1}\right) = MC_i\left(hV_{i+1} - 4{,}187T_i\right) + 4{,}187csol\left(T_i - T_{i+1}\right) \tag{8}$$

$$\left(MC_{j-2} - MC_{j-1} - MS_{j-1} + MV_{vd}\right)\left(hV_{j-1} - hL_{j-1}\right) + MC_j\left(hV_j - 4{,}187T_j\right) = MC_{j-1}\left(hV_j - 4{,}187T_{j-1}\right) + 4{,}187csol\left(T_{j-1} - T_j\right) \tag{9}$$

$$MV_{vd} = ML_{cd} + MV_{rec} \tag{10}$$

$$MV_{vd}hV_j = ML_{cd}hL_j + MV_{rec}hV_{rec} \tag{11}$$

Enthalpy of compressed vapor hV_{rec} may be calculated by Eq. (12) if the isentropic compressor efficiency (η_c) is known.

$$\eta_c = \frac{hV_{recs} - hV_j}{hV_{rec} - hV_j} \tag{12}$$

Where:

- hV_{recs}: specific enthalpy of the vapor at effect pressure j and with the same entropy vegetal of the vapor formed in the effect i [kJ/kg];

Power recompression (W_c) is calculated by Eq. (13). Saved steam goes to the second stage of the turbine to generate additional power (W_a), that is calculated by Eq. (14).

$$W_c = MV_{rec}\left(hV_{rec} - hV_j\right) = MV_{rec}\frac{1}{\eta_c}\left(hV_{recs} - hV_j\right) \tag{13}$$

$$W_a = MV_{veeco}\,\eta_t\left(hV_{e1} - hV_{e2s}\right) \tag{14}$$

Where:

- MV_{veeco} : mass flow of saved steam by the new evaporator configuration [kg/s];
- η_t : isentropic turbine efficiency;
- hV_{e1} : specific enthalpy of the steam extracted from the first stage of the turbine [kJ/kg];
- hV_{e2s} : specific enthalpy of the steam exhausted from the second stage of the turbine [kJ/kg];

3. CASE STUDY

In this work is presented a case study of a plant that has an evaporation system including five effects and possibility for vegetal vapor bleedings until the third effect. Higa and Luiz (2010) studied this system and proposed modifications in evaporator bleedings to reduce the global consumption of the process vapor (Tab. 1). Although modifications on evaporator bleedings reduce global consumption of the process vapor, retrofit in the surfaces of the heat transfer exchangers may be required in order to allow the operation using vegetal vapor of lower pressure. The same proposals about bleedings of vegetal vapor presented by Higa and Luiz (2010) may be applied to process using mechanical recompression, but with no retrofit in the surfaces of the heat transfer exchangers.

Table 1. Extraction (bleedings) configuration of vegetal vapor (Higa and Luiz, 2010).

Bleedings proposal	MS_1 (kg/s)	MS_2 (kg/s)	MS_3 (kg/s)	heat transfer surface - MEE (m^2)
Initial Situation (IS)	26.8	5.0	4.4	14536
II	17.0	14.8	4.4	15214
III	17.0	11.0	8.2	15365
IV	7.0	21.0	8.2	16167

The evaporation system studied concentrates 117 kg/s of sugarcane juice from 14.6 Brix to 60.0 Brix. Juice enters in evaporator at 117ºC and leaves at 67ºC, according to the work pressures and temperature in the effects of the evaporation system (Tab. 2). In the case of mechanical recompression from second effect to the second effect (RCP:2-2), vegetal vapor pressure is increased from the 0.1191 MPa to 0.1497 MPa. In the case of recompression from the third effect to the second effect (RCP:3-2), vegetal vapor pressure is increased from 0.0885 MPa to 0.1497 MPa.

Table 2. Effect Pressure and temperature in the MEE.

Effect	Pressure (MPa)	Temperature (^oC)
Inlet	0.1804	117
1st	0.1497	111
2nd	0.1191	105
3th	0.0885	96
4th	0.0580	85
5th	0.0274	67

The cogeneration cycle in this study works with two stages of turbine and provides steam to the evaporation system. Boiler generates steam at 480ºC and 6,7 MPa to the first stage of the turbine. After to produce power in the first stage, steam is extracted at 0,25 MPa to the process, and the remainder produces more work in the second stage of the turbine, until to be exhausted at 0,016 MPa.

3.1 Results

Expressive gains were observed after many simulations, but only in vapor recompressions from the third to the second effect and from the second to the same effect. In Table 3, results from modifications proposed by Higa and Luiz (2010) are compared with results to the same modifications from the previous work combined with recompression system applied in the present study.

Table 3. Simulation results.

System	Bleedings proposal	MV_{ve} (kg/s)	MV_{vesco} (kg/s)	MV_{rec} (kg/s)	W_c (kW)	W_a (kW)	W_{liq} (1) (kW)
Without recompression (WRCP)	IS	40.95	0	-	-	-	-
	II	39.12	1.83	-	-	603	603
	III	38.37	2.58	-	-	848	848
	IV	36.50	4.45	-	-	1462	1462
Recompression from second to second effect (RCP:2-2)	IS	33.11	7.84	38.7	2086	2575	489
	II	33.31	7.64	28.7	1547	2511	964
	III	33.33	7.62	24.9	1342	2504	1162
	IV	33.53	7.42	14.7	792	2439	1647
Recompression from third to second effect (RCP:3-2)	IS	32.73	8.22	19.6	2121	2699	578
	II	33.04	7.91	14.5	1569	2598	1029
	III	33.09	7.86	12.6	1364	2582	1219
	IV	33.40	7.55	7.4	801	2480	1679

(1): $W_{liq} = W_a - W_c$.

It is possible to observe in Tab. (3) and (4) when there are no modifications compared to the initial situation (IS), an additional electrical energy of 578 kW in the cogeneration system. Including the modifications of bleedings and recompression 1679 kW can be generated (Bleedings proposal: IV; RCP 3-2). However, in this case the recompression loses efficiency, because without it is already possible to get the surplus of 1462 kW (Bleedings proposal: IV; WRCP). In other words, the increase by recompression is only of 217 kW. This efficiency loss occurs due to pressure difference between the effects, increasing need for power to mechanical recompression.

Table 4. Gain of excess generation power.

Bleedings proposal	WRCP	RCP:2-2		RCP:3-2	
	W_{liq} (1) (kW)	W_{liq} (1) (kW)	Gain (kW)	W_{liq} (1) (kW)	Gain (kW)
IS	0	489	489	578	578
II	603	964	361	1029	426
III	848	1162	314	1219	371
IV	1462	1647	185	1679	217

(1): $W_{liq} = W_a - W_c$.

4. CONCLUSIONS

The use of mechanical recompression applied to the multiple effect evaporator may be a resource in order to reduce significantly the thermal energy consumption from a sugar and alcohol plant. Moreover, it is possible to have an expressive increase in surplus of electrical power from cogeneration systems installed on this type of the industrial plant. In this work was verified that the utilization of mechanical recompression of vegetal vapor associated to the increase of vegetal vapor extracted to the process from the last effects of multiple effect evaporator (MEE), as proposed in previous works, tends to increase the potential of power generation. However, it was observed that the gain is more significant, although it is not higher, when the vegetal vapor extracted for the process occurs in the first effects of the evaporator system.

5. ACKNOWLEDGEMENTS

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