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Thermal integration of multiple effect evaporator in sugar plant

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ABSTRACT

Besides the largest energy consumption in the process of sugar production, evaporation also presents many opportunities of thermal integration with the remaining of the process. That occurs due to the possibility of making use of the vapor generated during the evaporation operation (vegetal vapor), as a heating source, from extractions to process. Regarding the thermal integration of the multiple effect evaporator (MEE), previous studies showed that, in general, the energy recovery is usually larger when extractions are practiced in the last effects of the operation. Although the results found can be used for development of new projects, as heuristic rules, the application has been limited due to the lack of understanding on the subject. In the present investigation, a study was carried out by defining equations that can be used as a reference for thermal integration projects, including MEEs. The equations are also helpful for elaborating a systematic way to apply pinch analysis in sugar plant with an algorithm.

1. Introduction

Basically, heat demand in sugar plants occurs in the following operations: juice heating, evaporation and crystallization. Although all the operations mentioned are necessary for the production process, evaporation is emphasized in the thermal integration aspect, not only due to the largest energy consumption, but also, due to the possibility of using the vapor generated in that operation (VV), as heating source to the remaining of the process. That is possible because the equipment used for juice concentration, that is, the multiple effect evaporator (MEE), is divided into several stages, using the heating steam from back-pressure turbines (ST), only in the first effect, thus allowing other effects to take advantage of the thermal energy of VV generated in the operation itself. As VV and the solution are in the same temperature at the end of each effect, and a temperature difference is necessary between the fluids to occur the heat transfer, the evaporation in an effect always happens in inferior pressure if compared to the previous effect. Then, there is an availability of VV in different levels of temperatures that can also be used to supply the process demand, through extractions (bleedings) from the effects (Fig. 1).

Besides the possibilities of alternative among the available technologies in the market, the differences in the configurations of a MEE can be established through the variation of the equipment effect number, effects in which the vapor extractions for the process occur and working temperature levels. Christodoulou [1] approaches the evolution MEE use along the time, mentioning the increase of the effect number to 6 or 7 in beet sugar process, as well as the increase of the temperature vapor for larger thermal use by recompression, while Ibarra and Medellín [2] suggest to adjust working temperatures for a better integration with the process.

Using vapor extraction to the process is relevant for reducing the energy consumption in sugar plants. Previous papers [3,4] showed that in multiple effect evaporators, thermal recovery is usually larger when vapor extractions occur from the last effects of that operation.

Considering that problem, an appropriate method for optimization of process integration and choosing the best configuration of MEE is necessary. In previous papers, pinch analysis [5–7] has been used effectively to evaluate industries processing beet [8] and sugarcane [2]; however, the fact of not understanding some difficulties has been limiting its application in the sector. The aim of this study was to define equations that can be used as reference for the projects of thermal integration involving MEEs, and can also contribute with more systematic use of the pinch analysis in sugar plants.

2. Pinch analysis review

Introduced by Linnhoff et al. [9], pinch analysis has as purpose to identify the optimum heat recovery of process and to establish the most promising options concerning cost of the heat exchanger network (HEN). The identification of possible opportunities of thermal integration can be visualized through the hot and cold composite curves (CCs) (Fig. 2a), which are combinations of the thermal streams of total process, in terms of their heat contents over each temperature level (Temperature × Enthalpy). Hot and cold CCs represent the energetic availability and the requirement

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Nomenclature

A	heat transfer area (m^2)
CC	composite curve
D_{VV}	heat demand in the temperature zone of evaporator operation (kW)
EF	evaporator effect
MEE	multiple effect evaporator
GCC	grand composite curve
M_p	mass flow rate of vegetal vapor extracted in each evaporator effect (kg/s)
N	effect number of multiple effect evaporator
q_{MEE}	restricted energy consumption of multiple effect evaporator (kW)
q''_{MEE}	restricted consumption estimation of q_{MEE} (kW)
Q_{MEE}	energy consumption of multiple effect evaporator (kW)
$Q^{total}_{evaporation}$	necessary energy for total evaporation (kW)
Q^{Pr}_{H}	target of process energetic consumption without evaporator including (kW)
$Q_{M_p i}$	process heat supplied by using vegetal vapor (kW)
Q^{Total}_{H}	target of energetic consumption in global process (kW)
$Q^{Total''}_{H}$	target of global consumption (kW)
ST	exhaust steam from back-pressure turbine
VV	vegetal vapor

Superscript

$''$	estimated value

Subscript

i	effect of multiple effect evaporator

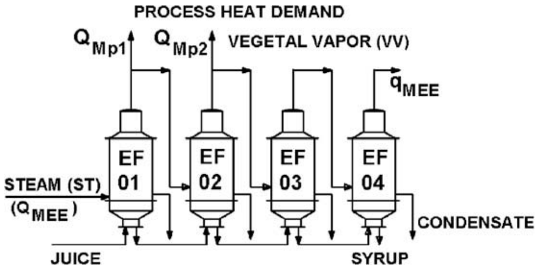

Fig. 1. Typical configuration of multiple effect evaporator (MEE).

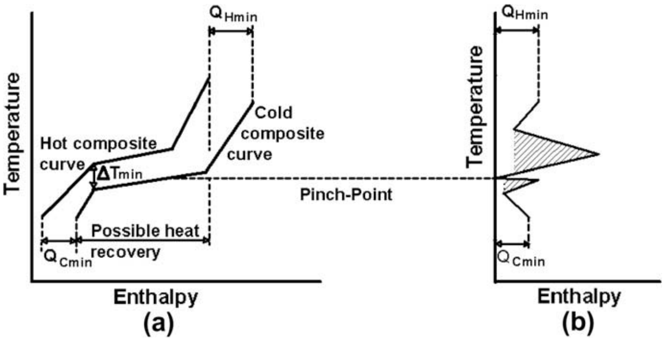

Fig. 2. (a) Composite curves (CCs) and (b) grand composite curve (GCC) [9].

of the global process, respectively, their overlapping indicates the maximum heat recovery of process, whereas the overshoots determine the minimum hot and cold utility requirements of the process (targets). The minimum temperature difference (ΔT_{min}), imposed by the project, with regard to capital cost, is the limit for the approximation between the curves and establishes the pinch-point. In application terms, it is relevant to observe that there should be no heat transfer across the pinch, because any transfer of heat implicates in increase from hot and cold utilities.

The grand composite curve (GCC) (Fig. 2b) is another tool also used in pinch analysis. That combines hot and cold CCs in a single curve, also through the sum of their heat content in each temperature level. For zero value of the enthalpy horizontal axis, the temperature of that point coincides with the pinch-point. Using GCC it is easier to observe that, in the temperature levels above the pinch, the process just needs hot utility, whereas below the pinch the demand is for cold utility. In addition, the dark areas indicate where the process can supply its own demand. In case of many utilities (multiple level utilities), it is possible to choose one of them, based on the closer temperature level to the demand, minimizing the heat transfer irreversibility. In this case, there is also the benefit of obtaining some work, as it would be the example of the steam turbine, which is able to generate power using the degradation from high to low steam pressure.

3. Composite curve and multiple effect evaporator (MEE)

According to Singh et al. [6], MEE has a conceptual problem for the constructions of CCs and GCC, since the minimum target utility is greatly affected by certain arrangement. The concentration required from the liquor can be achieved with a variety of effects and extractions of VV configurations, each leading to a different CCs and GCC. Moreover, as each effect of MEE produces almost the same amount of vapor that it consumes, although in lower temperature and pressure, at the same time it produces work in form of solid/liquid separation, the latter authors consider that MEE can be seen as a backpressure turbine, an utility supplier for the thermal integration, being completely excluded in the GCC construction. Since there are several effects, heat flows must be classified as utilities in multiple temperature levels, and the equipment configuration should be defined according to the thermal demand of GCC.

In a similar trend, Urbaniec et al. [7] considers that the way for solving the energy integration problem, simultaneously designing the MEE configuration, must be through the decomposition of the thermal system, assuming the existence of two interactive sub-systems: MEE and the remaining of the process. Therefore, the vapor produced in the evaporator can also be seen as utility for determining the minimum consumption according to temperature level corresponding to the evaporation effect of VV. Only after the configuration definition is adjusted to the process thermal demand, CCs and GCC are constructed, including all the thermal streams of MEE.

4. Multiple effect evaporator integration

Basically, thermal evaluations of the present work are carried out in three stages by adopting a similar procedure as Singh et al. [6] and Urbaniec et al. [7], described as follows.

1st stage: In the first analysis stage, GCC process is built (Fig. 3) by excluding MEE, to determine the consumption target in those

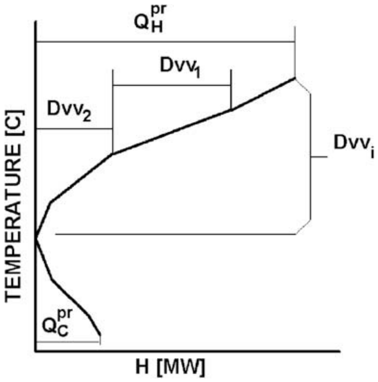

Fig. 3. Process grand composite curve excluding MEE.

conditions (Q_H^{Pr}). This also makes possible the rising of the heat demand profile of the process (D_{VV}) in the MEE temperature levels, allowing that the equipment configuration can be determined in a second stage, thus making possible the best thermal integration with the remaining of the process.

After the consumption equipment (Q_{MEE}) is determined without integration with the remaining of the process and extraction of VV, the plant global consumption for the process can be described by Eq. (1):

$$Q_H^{Total} = Q_H^{Pr} + Q_{MEE} \tag{1}$$

Second stage: The configuration of MEE is determined by including the number of effects (N), the temperatures and the heat supply to the process, through the extractions of VV (Q_{M_pi}) in each effect (i).

As the definition of MEE in this second stage seeks just for a configuration that satisfies the heat demand in the operation level of the equipment ($\sum_{i=1}^{N} D_{VVi}$), the occurrence of that integration can be admitted. Thus, if the mass and energy balances is accomplished, and the consumption of the equipment (Q_{MEE}) in these new conditions are determined, the equation is:

$$Q_H^{Total} = Q_H^{Pr} - \sum_{i=1}^{N} D_{VVi} + Q_{MEE} \tag{2}$$

The consumption of MEE can be defined in two terms, the first, referring to the energy supplied to the process (Q_{M_pi}), and the second, to the consumption restricted to MEE (q_{MEE}), it can be described as:

$$Q_{MEE} = \sum_{i=1}^{N} Q_{M_pi} + q_{MEE} \tag{3a}$$

or:

$$q_{MEE} = Q_{MEE} - \sum_{i=1}^{N} Q_{M_pi} \tag{3b}$$

Substituting (3a) in (2), it is obtained that:

$$Q_H^{Total} = Q_H^{Pr} - \sum_{i=1}^{N} D_{VVi} + \sum_{i=1}^{N} Q_{M_pi} + q_{MEE} \tag{4}$$

Once the VV extractions were determined through the heat demand of the process, it is considered that:

$$\sum_{i=1}^{N} Q_{M_pi} = \sum_{i=1}^{N} D_{VVi} \tag{5}$$

Resulting in:

$$Q_H^{Total} = Q_H^{Pr} + q_{MEE} \tag{6}$$

For determining the minimum consumption target of the global process, this equation makes the construction of many CCs and GCCs unnecessary, thus, allowing to obtain the target just examining MEE. Therefore, after defining the minimum consumption of the process, without inclusion of MEE (Q_H^{Pr}), in the first stage, the MEE configuration allowing the minimum consumption of utility of the global process (Q_H^{Total}) will be the one that minimizes the restricted consumption to MEE (q_{MEE}).

That consumption can be analyzed clearly through the GCC construction (Fig. 4) of an isolated MEE of the process. Although the heat supplied, in an effect, does not produce exactly the same amount of energy through VV, due to the concentration changes and specific heat of the juice, and due to the flash vapor produced by the pressure reductions among the effects of MEE, in the proposed curve, to make the understanding of the subject easier it is considered that each effect produces exactly the same amount of energy. For instance, the configuration has four effects, thus allowing extracting VV until the third one. Dashed lines represent the heat demand for the juice concentration, whereas the dotted lines represent the energy availability from VV, produced in each effect.

The curves show that if there is no VV extraction for the process (Q_{M_pi}), the rectangles representing the energy demand and the availability will have the same size in different temperature level for all MEE effects. Moreover, the VV energy from the last effect, representing exactly the restricted consumption to MEE (q_{MEE}) from Eq. (3), which also corresponds to the heat dissipated in a condenser, will not be used for the process. It is relevant to know that the minimizing that dissipation will represent the global reduction of the process consumption, according to the Eq. (6).

For minimizing the restricted consumption to MEE (q_{MEE}), through the Eq. (3), it is necessary to accomplish complete simulations of MEE, involving a great number of variables in each configuration. However, an approximate value of that variable can be obtained through simplified calculations. As the necessary heat for the complete evaporation ($Q_{evaporation}^{total}$) is the sum of all the cold streams in the graph (Fig. 4), the following equation can be written:

$$Q_{evaporation}^{total} = \sum_{i=1}^{N} iQ_{M_pi} + Nq_{MEE} \tag{7a}$$

or:

$$q''_{MEE} = \frac{\left[Q_{evaporation}^{total} - \sum_{i=1}^{N} iQ_{M_pi}\right]}{N} \tag{7b}$$

where, q''_{MEE}: estimated value of restricted consumption of MME (q_{MEE}).

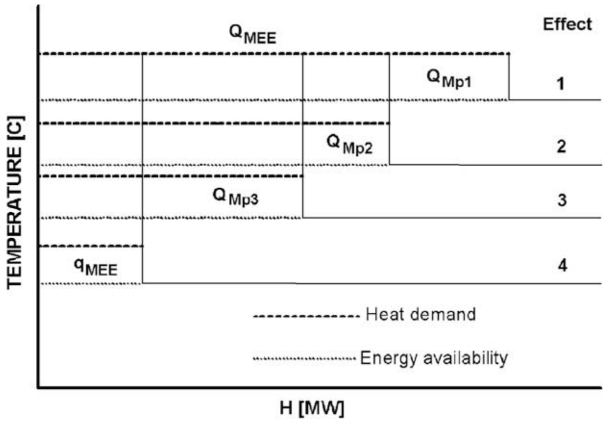

Fig. 4. Grand composite curve of MEE.

Table 1
Streams data

Stream	Type	Temperature (°C)		Specific heat (kJ/kg °C)	Flow rate (kg/s)	Heat flux (kJ/s)
		Inferior	Superior			
1	Cold	35	105	3.91	99.2	27475
2	Cold	35	105	3.91	66.1	18317
3	Cold	98	115	3.94	81.9	5482
4	Hot	32	98	3.98	57.9	15209
5	Cold	62	62	–	–	27792

This equation considers some approximations because the necessary heat for total evaporation ($Q_{\text{evaporation}}^{\text{total}}$) has a small variation, and the heat supplied to the process ($Q_{M_p i}$) is not exactly the same in the effects, as previously mentioned. Even so, this equation can help in the attempts for minimizing the restricted consumption to MEE. It can be observed that the reduction of q''_{MEE} is possible, not only by the increase of the effect number (N), but also by the increase of VV and $Q_{M_p i}$ supplied to the process, and the reduction is more significant for the use of VV in the last effects of MEE.

The Eq. (6) can also be redefined, through the inclusion of Eq. (7):

$$Q_{\text{H}}^{\text{Total}''} = Q_{\text{H}}^{\text{Pr}} + \frac{\left[Q_{\text{evaporation}}^{\text{total}} - \sum_{i=1}^{N} iQ_{M_p i}\right]}{N} \tag{8}$$

This equation is in agreement with results obtained in previous studies that conclude that the vapor extractions should be practiced in the last effects of the evaporation, where the temperature levels are closer to the demand, so that the steam consumption of the global process is minimized.

If VV, from the last effect, is completely used in other heating demands, the restricted consumption will be minimized, also reducing the global consumption target of the process. For the MEE configuration definition, Singh et al. [6] include in the same graph, rectangles representing each effect and process GCC, excluding the equipment. In that case, for a more efficient use of the available heat, the rectangles representing MEE must be positioned entirely above or below the pinch-point, avoiding the heat transfer across the equipment. Such measured is used to minimize the MEE restricted consumption.

A condition that must be considered when choosing MEE configuration is the restriction of the total availability of vapor and the necessary areas for heat transfer. It is observed that the total water evaporated, established by input and output juice concentration, is not completely available for the process, but it is necessary to consider that a part is used for the internal supply in each equipment effect.

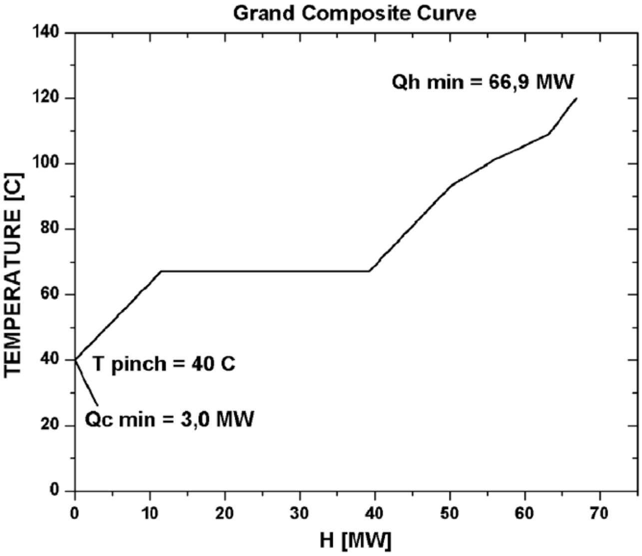

Fig. 6. Process grand composite curve excluding MEE.

Table 2
MEE constant data

	Temperature (°C)	Concentration (Brix)	Flow rate (kg/s)
Input	115	15	81.9
Output	–	65	18.9

Table 3
MEE temperature data according to effect number

No effects	Effect temperature (°C)				
	1	2	3	4	5
3	115	100	72	–	–
4	115	104.2	88.5	54	–
5	115	107.2	97.4	83	54

It is possible to get a better VV use, if the MEE effect temperatures are adjusted for meeting the demand. However input and output maximum temperatures are necessary as restriction, because if they are very high, formation problems, regarding color, can cause production losses.

Another restrictive factor, in the MEE thermal integration with the process, is the relation capital-costs invested in heat transfer

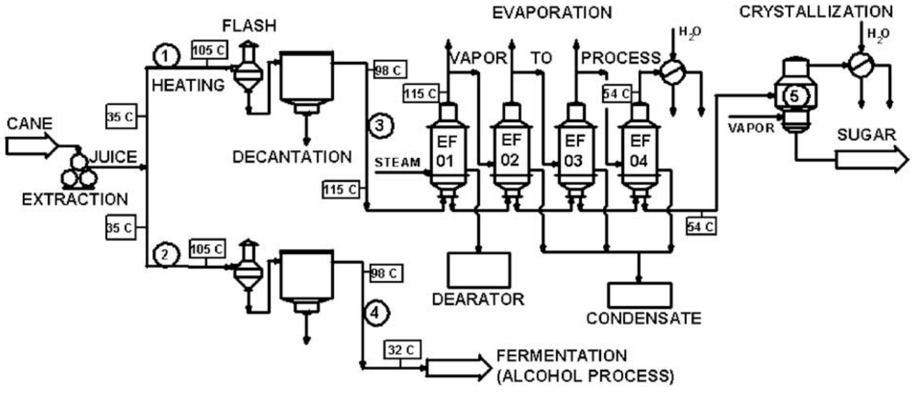

Fig. 5. Sugar production process.

Table 4
MEE energy consumption process, without integration and evaporation total

No effects	Q_{MEE} (kW)	Q_{H}^{Total} (kW)	$Q_{evaporation}^{total}$ (kW)
3	45003	111857	136857
4	32104	98958	134802
5	24790	91644	134735

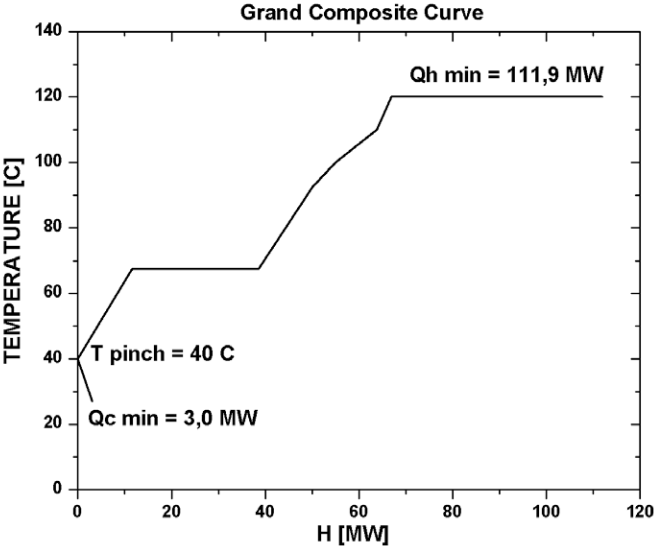

Fig. 7. Process GCC, including MEE, but without VV extractions (three effects).

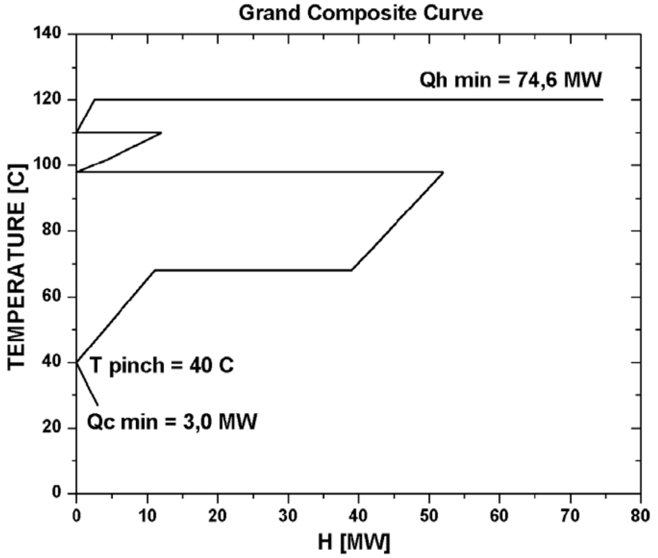

Fig. 8. Process GCC, with VV extraction until the second effect (three effects).

areas, and also, the thermal-energy cost. The MEE heat transfer areas estimate can be determined after the choice of the equipment configuration, by using equations of heat transfer overall coefficients used in manuals about sugar production [10–12].

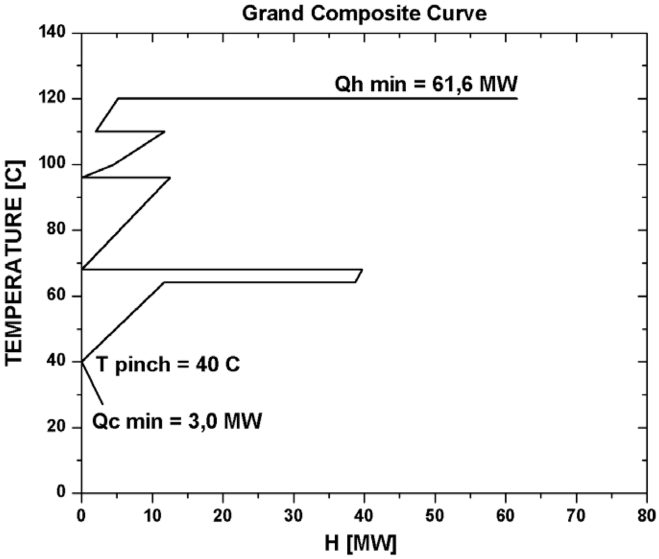

Fig. 9. Process GCC, with VV extractions until the third effect (three effects).

Table 5
VV demand and offer (three effects)

Simulation	Process demand for MEE effects D_{VVi} (kW)			VV energy availability in the effects $Q_{M_{p}i}$ (kW)			Q_{MEE} (kW)
	1	2	3	1	2	3	
3-1	63629	–	–	63629	–	–	89020
3-2	12039	51590	–	12039	51590	–	71361
3-3	12039	12357	39233	9974	12357	39233	56394

Table 6
Restrict and total consumption of MEE (three effects)

Simulation	q_{MEE} (kW)	$q''_{MEE}(kW)$	$Q_{H}^{Total}(kW)$	$Q_{H}^{Total''}(kW)$	Error (%)
3-1	25391	24409	92245	91263	−1.1
3-2	7732	7213	74586	74067	−0.7
3-3	−5170	−5177	61684	61677	−0.01

Third stage: The hot and cold composed curves are constructed in the third stage, also by including to the process, the external consumption of MEE and the vapor extraction streams. The inclusion of all thermal streams to the process in hot/cold CCs, and in GCC, enables the method to indicate which streams should exchange heat among themselves. It was demonstrated previously [13] that, if the heat network exchanger is configured in such a way that the streams involved in the equipments are positioned vertically at the composite curves, then the capital cost of heat transfer overall area tends to be minimized.

Except for Singh et al. [6], in the previous studies regarding sugar process, all the internal thermal streams of MEE are included in the construction of CCs and GCC processes. However, those streams are usually gotten from a known MEE configuration, in which the energy balances of the equipment is previously calculated, by considering pre-defined streams that change heat among each other. Thus, when the CCs and GCC diagrams indicate that one internal stream must change heat with another stream, that new configuration option also changes both, the energy balance and the thermal internal loads of the evaporator. Consequently, CCs and GCC are not the same, once they have a different format from the considered initially for the evaluation, so there is a need for reconstruction them.

Since the streams exchanging heat are already defined in the MEE internal configuration, it is not necessary to include them in the composite curves, thus only the demand of first effect and VV streams to process are traced in the graphs.

Table 7
VV demand and offer (four effects)

Simulation	Process demand for MEE effects D_{VVi} (kW)				VV energy availability in effects Q_{M_pi} (kW)				Q_{MEE} (kW)
	1	2	3	4	1	2	3	4	
4-1	63629	–	–	–	63629	–	–	–	81866
4-2	9293	54336	–	–	9293	54336	–	–	68231
4-3	9292	8092	46244	–	0	0	46244	–	44544

Table 8
Restrict and total MEE consumption (four effects)

Simulation	q_{MEE} (kW)	$q''_{MEE}(kW)$	Q_H^{Total} (kW)	$Q_H^{Total''}$ (kW)	Error (%)
4-1	18237	17793	85091	84647	−0.5
4-2	4602	4209	71456	71063	−0.6
4-3	−1700	9825	65154	65872	1.1

5. Case study

The present study focuses a typical sugar cane factory, processing 480 tc/h (tc: ton of cane). For the application of the method, a minimum temperature difference of 10 °C was chosen, in order to limit the heat transfer. The properties of the steam process is due to the level of pressure going out of turbines, usually used as heat source, and in this case of 0.25 MPa (∼127.4 °C; h_{fg} = 2.181.6 kJ/kg: latent heat of the steam).

The individual thermal loads of the streams were calculated, by using temperature and flow rate juice data, whereas, for the crystallization, the thermal consumption was already known (Table 1). The schematic plant for the thermal evaluation t is illustrated in Fig. 5.

1st stage: In the first stage of the analysis, the GCC of the project (Fig. 6) was constructed by excluding MEE for determining the minimum consumption target in those conditions ($Q_H^{Pr} = 66854$ kW), and also, for observing the VV demand profile in the MEE temperature levels.

Second stage: Three cases of MEE configurations were analyzed (A, B, C) in the second stage, by using third, fourth and fifth effects, respectively. The variables verified were the demand and VV extractions, according to their temperatures and availability, whereas the input temperature and the flow rate input and output concentrations are constant (Table 2). Although the intermediate effect temperatures (Table 3) can be chosen according to process demand, they were calculated in order to maintain a homogeneous distribution of pressure among the MEE effects.

The energy consumption of the operation for the process, without VV extractions, are in Table 4, and that value is used to calculate the necessary heat for obtaining the complete evaporation.

5.1. Case A – (three effects)

Analyses from first, second, and third effects, using extractions VV, were accomplished in case A. The output temperature, for possible process use, was chosen in 72 °C. The complete MEE simulations to determine the equipment consumption and GCC constructions were unnecessary to obtain the minimum process demand (target). Anyway, GCCs (Figs. 7–9) were constructed and calculations (Tables 5 and 6) were accomplished to compare the equations results Eqs. (3)–(7) and (6)–(8).

Table 10
Restricted and total consumption of MEE (five effects)

Simulation	q_{MEE} (kW)	$q''_{MEE}(kW)$	$Q_H^{Total}(kW)$	$Q_H^{Total''}(kW)$	Error (%)
5-1	14270	14221	81124	81075	−0.06
5-2	3217	2961	70071	69815	−0.4
5-3	−901	−219	65948	66635	1.1
5-4	−2184	−669	64670	66185	2.3

Table 11
MEE area estimate (three effects)

Simulation	A1 (m^2)	A2 (m^2)	A3 (m^2)	A_{TOTAL} (m^2)	Q_{MEE} (KW)	q_{MEE} (kW)	Q_H^{Total} (kW)
3-0	1548	1675	1903	5126	45003	45003	111857
3-1	3285	1058	1159	5502	89020	25391	92245
3-2	2541	2831	482	5854	71361	7732	74586
3-3	1959	1806	1512	5277	56394	−5170	61684

Table 12
MEE area estimate (four effects)

Simulation	A1 (m^2)	A2 (m^2)	A3 (m^2)	A4 (m^2)	A_{TOTAL} (m^2)	Q_{MEE} (KW)	q_{MEE} (kW)	Q_H^{Total} (kW)
4-0	1090	1622	1630	1809	4691	32104	32104	98958
4-1	2973	1006	1040	1104	6123	81866	18237	85091
4-2	2417	4012	418	409	7256	68231	4602	71456
4-3	1531	2404	3070	146	7151	44544	−1700	65154

According to expectancy, the results showed that, when VV extractions are available in the last effects, the global consumption of the process tends to decrease. For VV extractions until the second effect (Simulation 3-1 and 3-2), the VV energy availability is enough to supply the process demands. It does not happen with extraction until the third effect (Simulation 3-3). In that case, the offer of the first effect was reduced to increase the availability in the last effects, in order to get larger reduction of steam consumption, as seen in Eqs. (7) and (8). An interesting result refers to the value of q_{EME}, that in the case of extraction, until the third effect is negative, thus reducing the global consumption target (Q_H^{Total})

Table 9
VV demand and offer (five effects)

Simulation	Process demand for MEE effects D_{VVi} (kW)					VV energy availability in effects Q_{M_pi} (kW)					Q_{MEE} (kW)
	1	2	3	4	5	1	2	3	4	5	
5-1	63629	–	–	–	–	63629	–	–	–	–	77899
5-2	7327	56301	–	–	–	7327	56301	–	–	–	66845
5-3	7329	6324	49978	–	–	0	0	45276	–	–	44371
5-4	7329	6324	6068	43910	–	0	0	0	34520	–	32336

Table 13
MEE area estimate (five effects)

Simulation	A1 (m^2)	A2 (m^2)	A3 (m^2)	A4 (m^2)	A5 (m^2)	A_{TOTAL} (m^2)	Q_{MEE} (kW)	q_{MEE} (kW)	Q_H^{Total} (kW)
5-0	837	1784	1843	1913	2149	8526	24790	24790	91644
5-1	2807	1106	1174	1246	1322	7655	77899	14270	81124
5-2	2363	6118	447	480	463	12234	66845	3217	70071
5-3	1525	3533	4968	197	217	10440	44371	−901	65948
5-4	1019	2400	2574	3324	264	9661	32336	−2184	64670

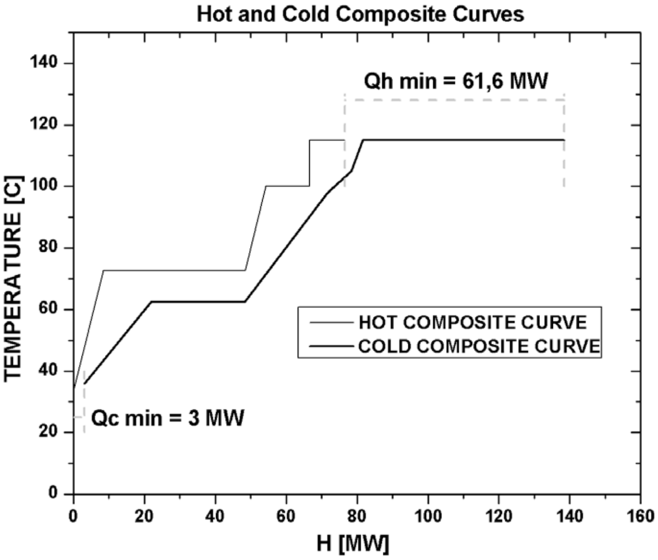

Fig. 10. CCs from the process, with extraction of VV up to the third effect (three effects).

to inferior values, even for process consumption target excluding the integration (Q_H^{Pr}).

5.2. Case B (four effects)

Analyses were accomplished in case B, by using VV until the third effect. The evaporator output temperature used was 54 °C, usual level in plants.

The results of Q_H^{Total} are better when VV used comes from the third effect, than when VV comes from the second and first effect. However, the results for the consumption target using VV until the third effect were worse than in the previous case (Tables 5 and 6: simulation 3-3). The reason for that can be observed in Tables 7 and 8 (simulation 4-3), although the total consumption of MEE (Q_{MEE}) is minor when using four effects, there is less energy available from VV, thus not supplying the process demand. Consequently, the restricted consumption to MEE (q_{MEE}) is larger in that case, thus increasing the minimum consumption target of the process total (Q_H^{Total}).

5.3. Case C – (five effects)

In case C, analyses were accomplished by using VV until the fourth effect (Tables 9 and 10). The output temperature used for fifth effect was the same, that is, 54 °C.

When the results of Q_H^{Total} are compared according to the effect number, it is observed, for extractions in the same effects, that the increase of effect number reduces the steam consumption target when VV is available, but not when the availability is minor than the process demand. For the proposed simulations, MEE areas are estimated in Tables 11–13, also including consumption for the equipment and for the total process.

5.4. Third stage

Cold and hot CCs configured with three effects and using VV, coming from the third effect, presented the best result, as shown in Fig. 10. It can be observed that VV streams for process heating are included, but MEE intern streams that change heat among each other are not. As previously mentioned, the VV is the availability for the process as multiple level utilities.

6. Conclusion

Previous studies have shown that, the energy recovery is larger when VV extractions of MEE, to supply process demands, occur in the last effects of the operation. In the present study, it was defined the equations that were used as reference for thermal designs, involving MEEs integration. The results confirmed their validity.

For all MEE configurations analyzed in this study, the simulations were accomplished, and GCCs were constructed for determining the minimum consumption target of the global process. After determining the minimum process consumption, without inclusion of MEE (Q_H^{Pr}) in the first stage, the MEE configuration, which allows the minimum utility consumption for the global process (Q_H^{Total}) will be the one that minimizes the restricted consumption of MEE (q_{MEE}).

The estimate equation, of the restricted consumption to MEE (q''_{MEE}), made possible to verify how both, the effect number and the VV extraction for the process demand, affect the total process consumption.

Although the trend to reduce thermal consumption is the increase the effect number or VV extractions for the process, it was verified that q''_{MEE} minimization is the most important to get the best thermal process integration.

An interesting result is that, for thorough use of VV, the minimum value of q''_{MEE} was not zero as it could be expected, but negative values were also obtained. Such the result is better in relation to the performance of the process regarding steam reduction. The main facts that occur are in relation to the pressure decrease among the MEE effects, which allows flash of VV, and to the latent heat steam, which increases when the temperature decreases in the MEE operation temperature levels.

The differences between estimated ($Q_H^{Total''}$) and real (Q_H^{Total}) consumption of the total process, are in relation the value of the necessary heat for complete evaporation ($Q_{evaporation}^{total}$), which was calculated with MEE simulation, without extractions, for each effect number (3, 4 and 5). That value does not show great variations, but, on the other hand, it is not also exactly the same for all the conditions, once there is a small variation according to the working temperatures, the effect number and VV extractions. However, to make the analyses easier, $Q_{evaporation}^{total}$ could also be calculated just once (e.g., for evaporation with only one effect). Nevertheless, that tends to increase the error of simulation. Anyway, the differences among the consumption target of the total process, estimated ($Q_H^{Total''}$) and real (Q_H^{Total}), can be considered small and accepted for the analyses accomplished.

Those equations have also allowed the elaboration of an algorithm that systematizes the use of pinch analysis in sugar and alcohol plants. Although, in present investigation all the MEE simulations were accomplished for comparing results, they could be obtained, directly, through the proposed equations to make the thermal analyses easier. For the case study, it was highly relevant that, the best result under the thermal view point, was obtained with only three effects in MEE, and the estimates for the heat transfer areas have also obtained the best result in that configuration.

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