Integrating Thermal Vapor Recompression in a sugar factory
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In 2017, following an expansion of the evaporation with 6 to 7 effects, Cosun Beet Company Dinteloord invested in a thermocompression system to further minimize the condenser losses of the evaporation. The thermocompresssion system consisted of 4 thermocompressors of different sizes, which were able to cover a range of 0 to 45 t/hr of vapor 3 from the evaporation section to exhaust steam conditions.
After some start-up problems in the first campaign, this investment has proven a cost-effective solution to reduce the fluctuating condenser losses further strongly.
In this paper the concept of the flexible thermocompression, the experiences and some results are discussed.

1. Introduction

The energy transition and reduction of the CO_2 emission is a major challenge for the beet sugar industry. The uncertainty of fossil fuel availability in recent years and subsequent increasing fossil fuel energy and CO_2 emission costs make it even more important to reduce fossil fuel consumption. Furthermore, not only the fossil fuels have fluctuated much recent years, but with the strong upcoming renewable electricity production by wind turbines and solar PV, the electricity prices also are starting to fluctuate more and more.
Cosun Beet Company has the ambition to become the world's greenest, most innovative and most successful sugar beet processor. Therefore, energy efficiency projects, other CO_2 emission reduction projects, and measures to adapt to the energy landscape are of utmost importance.

In 2016 Cosun Beet Company Dinteloord (CBC Dinteloord) increased the 6-effect evaporation to a 7-effect evaporation using falling film plate evaporators for the first 3 effects. This was part of a program to both increase the beet processing capacity of the factory while at the same time reduce energy consumption. [1]
Despite this investment it was expected that the condenser losses, since they can fluctuate a lot, would at times be zero but at other times still be significant. See Fig 1 for the condenser losses at CBC Dinteloord in 2016 after the implementation of the 7-effect evaporation.
To further reduce these strongly fluctuating condenser losses in 2017 an additional thermocompression set, consisting of 4 thermocompressors, was implemented.

2. Reduction fluctuating evaporation condenser losses

Any reduction (or increase) in the steam demand in the sugar factory will have an impact on the process efficiency of the evaporation section. The process efficiency of the evaporator station is reflected in the so-called condenser losses of the evaporation. The condenser losses are the vapors that are not used within the process but must be sent to the condenser. From an energy point of perspective, the condenser losses in the evaporation preferably are close to zero, whilst maintaining an as high as possible thick juice or standard liquor brix to the crystallization.
Any water evaporation in the evaporation section that can be achieved without condenser losses can

be considered as “free water evaporation”. If the heat or vapor requirements of the process are fulfilled by bleeding the vapors from a suitable evaporator effect, these vapors will have evaporated in the previous effects water without almost any additional energy cost.

The condenser losses however typically are far from constant as can be seen in Fig 1. Any reduction in the vapor demand of the sugar process will increase the condenser losses. Any increase in the vapor demand will decrease the condenser losses. Furthermore, the condenser losses can fluctuate strongly due to process fluctuations, disturbances, or other operational settings.
The condenser losses fluctuate to smaller or larger extent because of for example:

- (setpoint) standard liquor brix
- fluctuating steam demand e.g. fluctuating steam demand batch crystallizers or performance heat recovery condensate
- Beet processing capacity
- Ratio white sugar to silo vs thick juice to thick juice storage
- Outside temperature
- Extraction draft
- Pol beet

Calculations showed for instance for the Cosun Beet Company Dinteloord factory that:

- An increase of the standard liquor brix setpoint from 77 to 78% increased the condenser losses with 5 t/hr.
- a 2 °C higher temperature of the limed juice due to a better performance of the heaters against condensate would increase the condenser losses with approximately 5 t/hr.
- The pol beet had a lower effect. With a pol beet of 16 instead of 17 pol the condenser losses were about 2 t/hr higher.

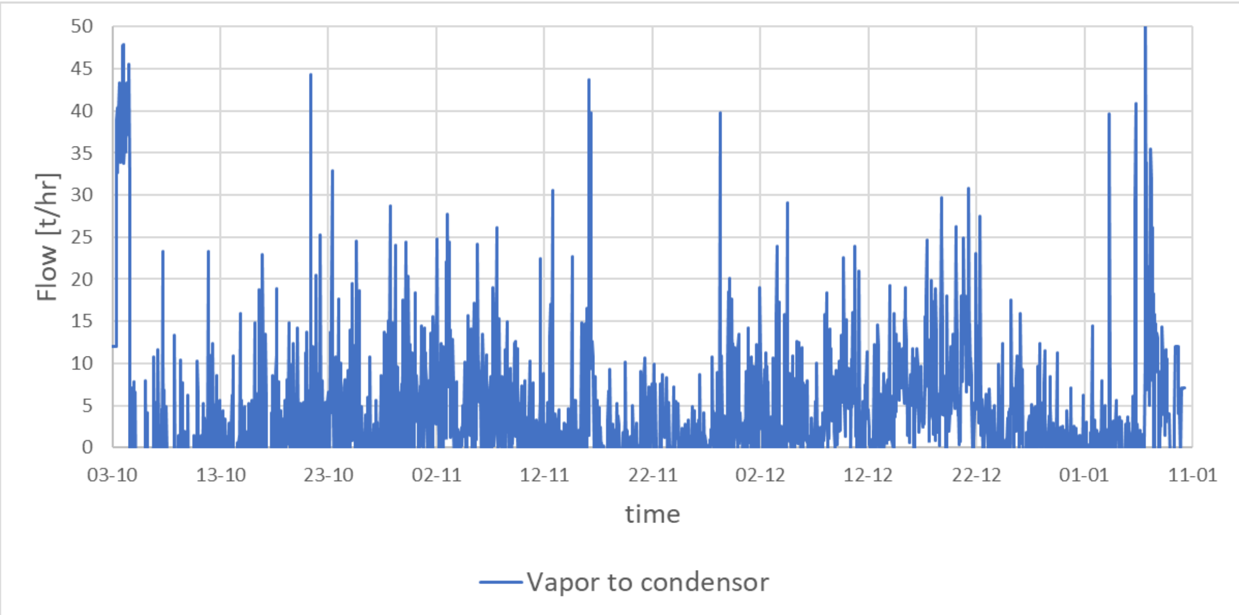


Figure 1: Condenser losses in 2016 campaign in the CBC Dinteloord factory after implementation 7 effect evaporation

Expanding the number of effects in a multi-stage evaporator can substantially reduce the condenser losses, and with that reduce energy consumption, but always in a stepwise fashion. The condenser losses always must be sufficiently high to allow such an investment to be feasible. Even after the implementation of the increase from a 6 to 7 effect evaporation there were still condenser losses foreseen at Cosun Beet Company Dinteloord as can be seen in Fig. 1.

Further minimizing the condenser losses to a level close to zero in the evaporation is only possible by flexible vapor recompression or other types of flexible water removal by for example membrane type processes like reverse osmosis. Alternatively, one could choose to overconcentrate and later dilute again by adding water.

3. Vapor recompression: MVR vs TVR

For the recompression of vapors there are two well-known technologies available, both of which have already been in use in the sugar industry [2]:

- Mechanical Vapor Recompression (MVR)
- Thermal Vapor Recompression (TVR)

Both techniques compress a lower pressure steam to a higher-pressure steam. With mechanical vapor recompression this is done mechanically by usually an electrically driven compressor or fan. Mechanical Vapor Recompression typically has a relatively high capital investment cost when compared to thermal vapor recompression. [3]
The turn-down ratio of mechanical vapor compressors is limited, typically not more than 50%. This would mean that several smaller mechanical vapor compressors would be required to be able to cover a full range of recompression capacities. This would have a negative impact on the CAPEX costs. Together with the relatively short beet campaign lengths this would make the use of mechanical vapor recompression not feasible for the reduction of the strongly fluctuating remainder of the condenser losses.

With thermal vapor recompression the vapors are compressed using the motive force of a high-pressure steam flow (motive steam) to recompress a lower pressure steam (suction steam). The mass flow of the discharge stream is at an intermediate pressure level and is the sum of the motive steam mass flow and the suction steam mass flow. This compression takes place in a thermocompressor or steam ejector, consisting of a nozzle, mixing chamber and diffuser (see Fig 2).

Figure 2: Schematic drawing thermocompressor (source: Körting)

The performance of the thermocompressor can be described by the so-called entrainment ratio which is defined as the ratio of the recovered suction steam quantity mass flow to the motive steam mass flow. A high entrainment ratio means that not much motive steam is used to recompress the suction steam. The entrainment ratio is dependent on the pressure levels, thermocompressor nozzles and diffuser pipe geometry. The entrainment ratio will be higher with lower compression ratios. The compression ratio is the ratio between the intermediate absolute discharge steam pressure and the absolute suction steam pressure.
Furthermore, the entrainment ratio will be higher with higher expansion ratio. The expansion ratio is the ratio between the absolute motive steam pressure and the suction pressure. [4]
The use of high-pressure motive steam in a thermocompressor will reduce the possibilities to produce electricity in the factory's steam turbines, which implies that less electricity can be exported or more electricity needs to be imported. Therefore, it is important that the motive steam to the thermocompressors is used as efficient as possible, which means that the entrainment ratio should be as high as possible.

The required recompression capacity fluctuates strongly, so the capacity of the thermocompressors needs to be regulated. But the capacity of individual thermocompressors can only limited be regulated by controlling the motive steam flow by either [5]:

a. using a control valve in the motive steam pipe before the thermocompressor, which regulates the flow and the steam pressure before the nozzle.
b. Using a nozzle needle which can change the diameter of the motive steam nozzle and with this the steam flow.

A control valve in the motive steam pipe to regulate the flow will always lower the motive steam pressure before the thermocompressor and thus lower the entrainment ratio.
In general, thermocompressors tend to have a narrow operating window in terms of flow control. Controlling the flow will quickly lead to a decreased efficiency of the thermcompressors.
The capacity can however also be regulated in a discrete manner by using multiple thermocompressors, in which the capacity is determined by switching thermocompressors on or off [2]. The thermocompressor can in this case always work at its optimal working point with the highest possible entrainment ratio.

4. Set-up thermocompressors Cosun Beet Company Dinteloord

The installation at Cosun Beet Company Dinteloord consists of 4 thermocompressors which recompress vapor 3 (~2 bara) of the evaporation section to exhaust steam pressures (~3.5 bara).
The thermocompressors were supplied by Körting. It was best to recompress vapor 3 since with the

replacement of the first 3 evaporator effects by evaporators with falling film plate evaporators in 2016, the pressure drop (per effect) over the first 3 evaporator effects was limited.

The 4 thermocompressors are designed to compress a total of 45 tonnes of vapor 3 per hour using about maximum 32 t/hr of motive steam (50 bar). The entrainment ratio is about 1.4. This makes it possible to correct for a maximum of ~ 20 t/hr of condenser losses.
The flow to the thermocompressors is not controlled by a flow control valve, but the thermocompressors are switched on or off based on the total required capacity. The desired capacity of the total set of thermocompressors is controlled by selecting a certain subset of thermocompresssors to be switched either on or off, based on the position of the control valves to the condenser.

At Cosun Beet Company Dinteloord was chosen to install 4 thermocompressors, with each subsequent thermocompressor 2 times larger as the previous one. This way 16 different discrete capacities can be generated with an interval of 3 t/hr suction vapor 3 (capacity smallest ejector) each. See table 1 and figures 3 and 4.
When implementing only 3 thermocompressors it would have been possible to have only 8 different capacity modes instead of 16. The additional cost of having one additional thermocompressor including appendages was however limited.
Although thermocompressors tend to have a narrow operating window in terms of flow control, or at the cost of decreased efficiency, control margin be difficult to control the flow without at the same time delivering too much on efficiency, this way it was possible to operate over a large discrete range without losing efficiency due to a worse entrainment ratio of the thermocompressors.

Since the outlet of the steam after the ejectors is strongly superheated at approximately 220 °C, the vapors must be cooled using a steam cooler, because of temperature resistance limitations of the downstream materials.

Table 1: Technical characteristics thermocompressors

	Load [%]	Vapor 3 [t/hr]	Motive steam [t/hr]	Discharge [t/hr]
Thermocompressor #1	6.7%	3	2.2	5.2
Thermocompressor #2	13.3%	6	4.3	10.3
Thermocompressor #3	26.7%	12	8.5	20.5
Thermocompressor #4	53.3%	24	17.0	41.0

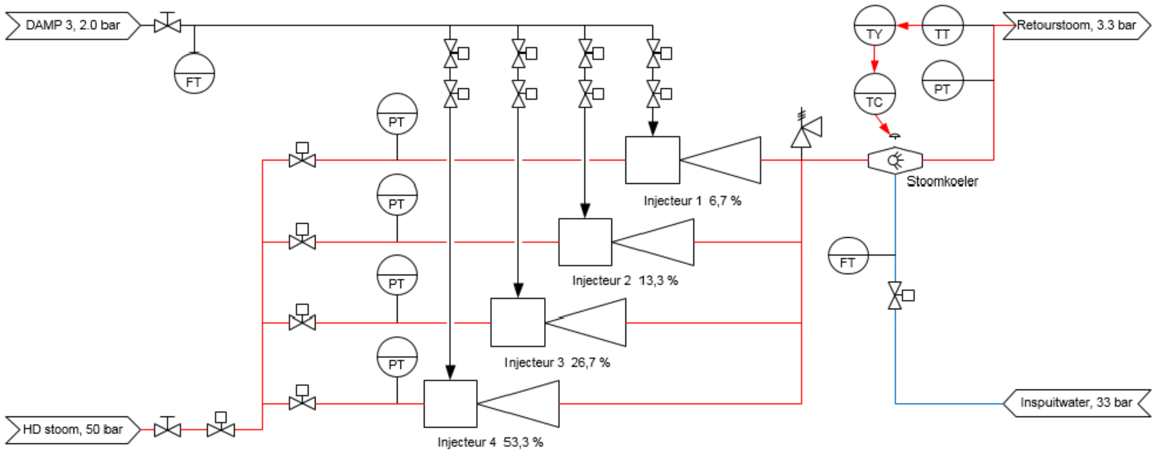


Figure 3: P&ID Thermocompressors Cosun Beet Company Dinteloord.

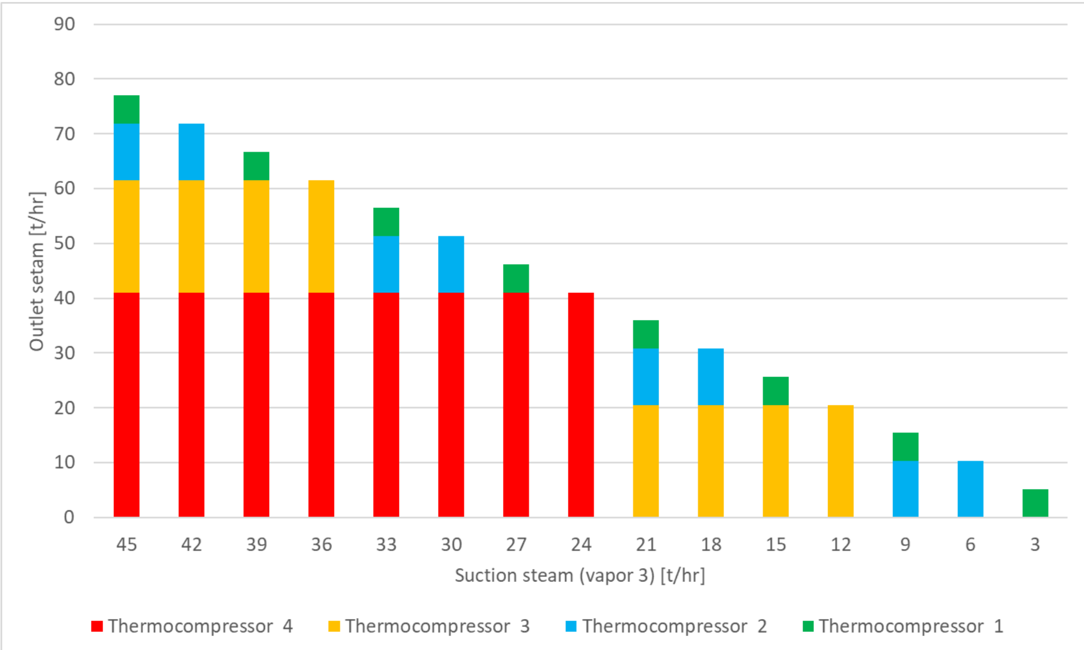


Figure 4: Capacities and on/off situation of thermcompressors over the whole capacity range (x-axis vapor 3 mass flow; y-axis: steam mass flow at exhaust steam pressure) *[6]*

Together with the investment in the thermocompressors it was decided to also increase the heat exchanger section of limed juice versus condensate. This to increase the temperature of the limed juice after heating with condensate with approximately 2 °C. With this additional heat exchanger the average condenser losses would increase with about 5 t/hr. This additional investment would increase the possible savings of the thermocompressors and improve the feasibility of the project.

The implementation of the thermcompressors also allowed in the subsequent years to reduce the steam consumption further by heat recovery measures of waste heat sources (e.g. carbonatation vapors), which otherwise would only have increased the condenser losses.

Figure 5: Thermocompressor installation during construction

5. Performance TVR system Dinteloord

The TVR system has proven to perform well over the last years. After the start-up problems in the first campaign where the TVR system could only be operated on 50% of the maximal capacity, the thermocompressors have operated well in the campaigns after.

Due to several reasons, over the last years the thermocompressors need to be used more and more, and very often operate on maximum capacity, as can be seen on the day average capacities of the TVR system (see Fig 6 and 7). The most important reason for this increased use were the further heat recovery measures implemented in the factory.

With the recent high gas prices the investment has proven to be a very feasible investment and valuable asset. From campaign 2017 to 2022 over 20 million Nm3 gas consumption was saved, which in part is due to a lower electricity production of about 660 GWh.

The scope 1 CO_2 emissions savings which can be accounted to the TVR system from campaign 2017 to 2022 are more than 37 kton CO_2 (Table 2).
The use of HP steam reduces however the electricity production by the steam turbines and with this the export of electricity to the grid. On national level this will have a negative impact since the reduced electricity production at the steam turbines must be compensated by electricity production elsewhere. When calculating this impact using the average CO_2 emission factor per MWh in the Netherlands over these years, the net savings on national level are approximately 13.7 kton CO_2.

Figure 6: Day average vapor 3 recompression beet campaign 2017 to 2019 [6]

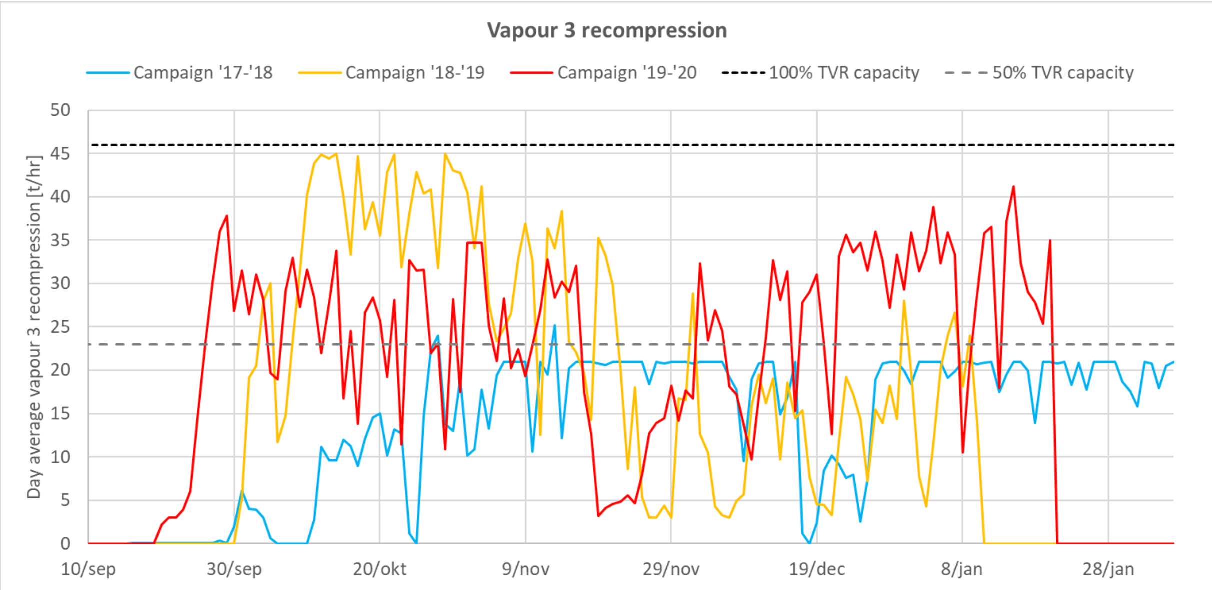


Figure 7: Day average vapor 3 recompression beet campaign 2020 to 2022

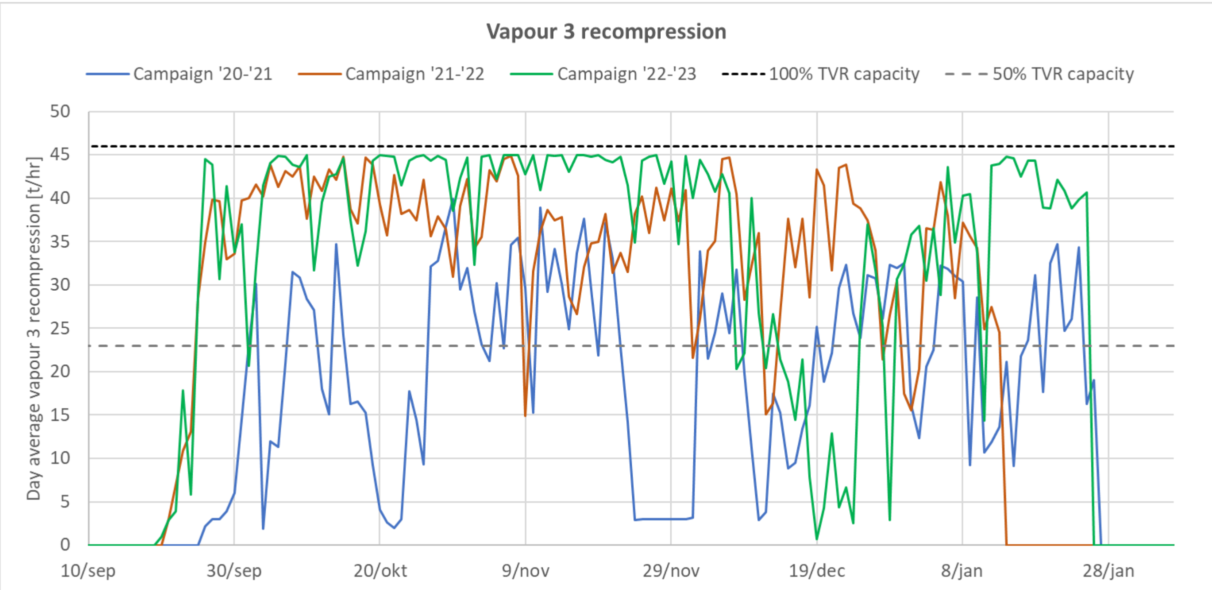


Table 2: Impact thermocompression on steam, gas, electricity production and CO2 savings

		'17-'18	'18-'19	'19-'20	'20-'21	'21-'22	'22-'23	Total
Vapor 3 recompression	k ton	52	59	74	63	99	113	460
Reduction condenser loss	k ton	22	25	32	27	42	48	196
Reduction gas cons.	M Nm3	2.40	2.23	3.56	2.62	4.52	5.46	20.8
Reduction El. Production	GWh	76	71	113	83	143	173	659
Reduction scope 1 CO2 emission	k ton CO2	4.3	4.0	6.4	4.7	8.1	9.8	37.2
Impact scope 2 emission (location based)	k ton CO2	-3.2	-2.9	-4.8	-2.8	-4.9	-4.9	-23.5

Net CO2 reduction	k ton CO2	1.1	1.1	1.6	1.9	3.1	4.9	13.7

An example of how the capacity of the thermocompression changes over time during a day (17/18 december 2022) is shown in figures 8 and 9. In these cases the thermocompressors were switched from maximum to minimum capacity in about 35 minutes. Here the factory must find a balance between the fluctuations in steam flow allowed over steam turbines, ejectors, steam boilers and evaporation.

Figure 8: Example on/off switching frequency thermocompressors on day basis (17/18-12-2022)

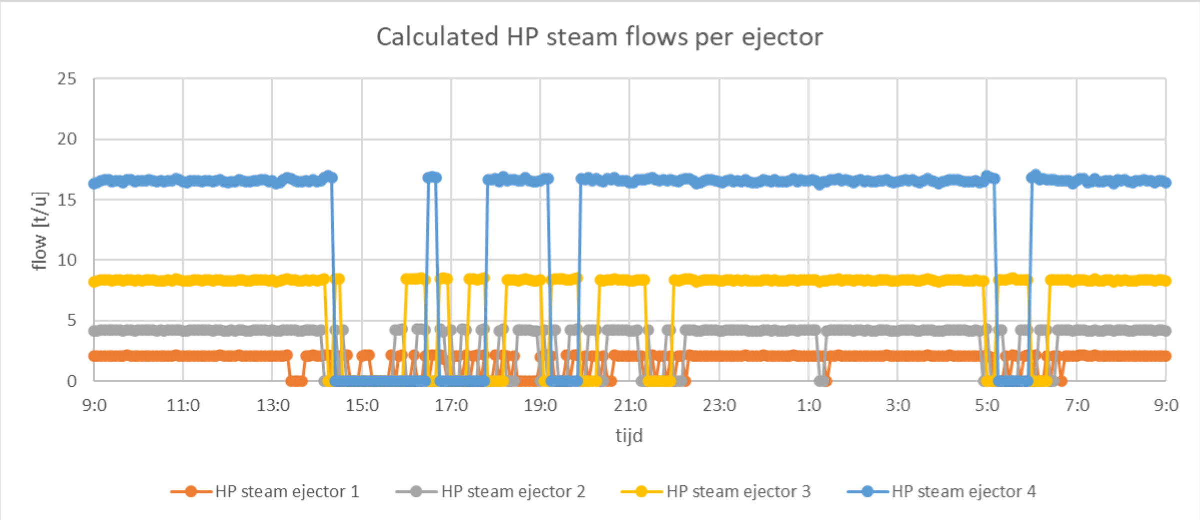
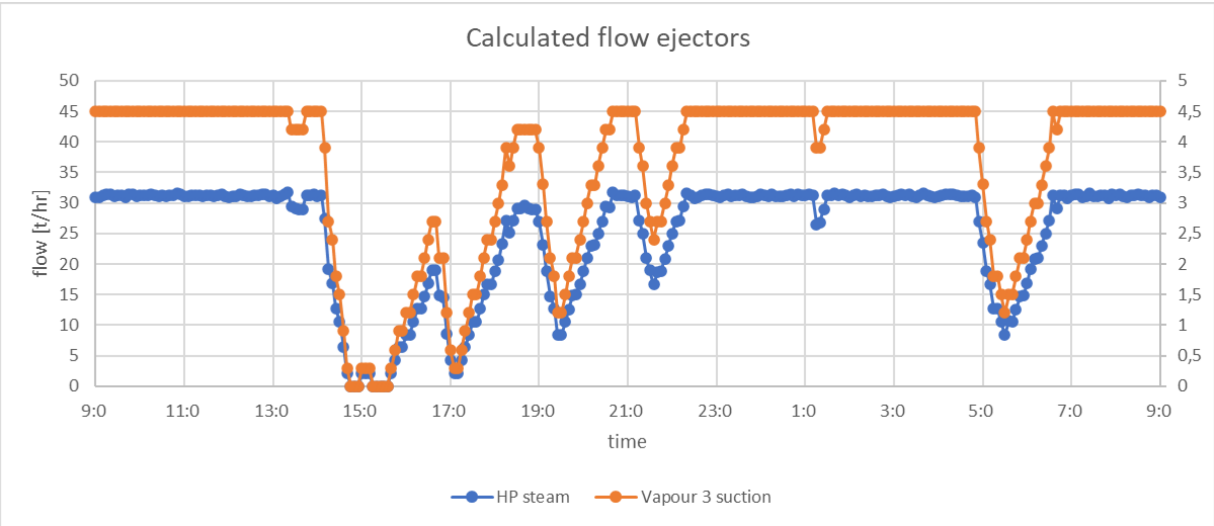


Figure 9: Example total calculated HP steam and suction flow on day basis (17/18-12-2022)



6. Experiences with the TVR system in Dinteloord

The commissioning of the Thermal Vapor Recompression system has taken place in the beet campaign of 2017. In each shift an operator was instructed how to work with the system and datasheets were filled in. In the beginning the injecting steps of 'high pressure steam' were taken manually. But very quickly the TVR system worked in the automatic mode. After commissioning the system increases the load based on the availability of condenser losses, the brix setpoint and energy export. It decreases the load when condenser losses are minimal and on the brix is above setpoint. The automatic tuning on energy import is not been taken in operation. In that case the operator has to take manual actions, if required.

In the first year the TVR system behaved quite nervous due to the short interval times between the transition to another step. By tuning these interval time settings, the whole system became more stable and fluctuations in output temperature and vapor pressure were reduced. The first malfunction was found in the vapor cooling of the system. The water injector was not able to control the temperature of the recompressed vapor at the highest area of steps.

A secondary malfunction what was observed were the sugar spores and coal found in the condensate of the first evaporation bodies. The demister of the third body was not able to catch out all the sugar spores. Especially in the high step area of the TVR the suction on the third vapor caused a high amount of sugar spores in the new recompressed vapor. Therefore, it was not possible to work in whole range of the TVR system during the first beet campaign. But only on 50% of the maximum load.

To prevent these sugar spores causing damage to the TVR system and other processes, an extra demister vessel was placed in front of the TVR system in 2018. This implementation made it possible to run the TVR system on its maximum load.

An important note when designing a vapor recompression system are the noise levels in the operational environment. The noise levels were been taken into account during the project and construction of the TVR system. A soundproof area has been built around the thermocompressors, to limit the noise in the immediate factory environment. However, it turns out that there is no point source. It appears that the noise load is carried through the piping of TVR the system due to the 49 bar high-pressure steam, which is injected supersonically. This makes wearing hearing protection in this environment absolutely mandatory.


These days the system hardly requires any attention from the operators. In the years the cooler and demister settings had to be tuned so the system was able to work in its whole range. Apart from that, the implementation of the TVR system went quite smoothly and over the 6 years of operation have proved to be a strong efficient tool to reduce the energy demand.

Although not practiced of yet towards the future the thermocompressors could also play a role in flexible minimizing the energy costs by decreasing the thermocompression capacity in favor of increased electricity production in the steam turbines at very high electricity costs. Possibly it could even be used to support to balance the electricity grid because of increasing unbalance due to renewable electricity production.

It was investigated whether the thermocompression would be a good option to implement also in the Cosun Beet Company Vierverlaten and Anklam factories. But since the situation at these factories is different in terms of available heating surface in the front-end of the evaporation, lower condenser losses, and other future plans, it was concluded that for now thermocompression was not the best option at this moment.

Acknowledgement
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