# THEORETICAL AND EXPERIMENTAL STUDY OF FLASH TANK IN A HEAT PUMP BASED STEAM GENERATION – PART 2

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## ABSTRACT

In industrial applications, heat is generally distributed using steam at the needed saturated temperature. An efficient method to generate steam is by using a highly efficient system for upgrading industrial waste heat and consuming decarbonised electricity. These devices may combine heat pumps and mechanical vapour compression MVC. A flash tank is a coupling device between these equipments. In a previous work (part 1 of this paper), a dynamic model of a flash tank was experimentally validated. In this study, we want to investigate the capacity of the flash tank to store energy and bring flexibility and robustness to the process with dynamic variations of waste heat sources and steam needs. The case study highlights the impact of the flash tank volume on energy performance and flexibility using a simplified model of a heat pump and MVC together with the dynamic model of the flash tank. Results show a good capacity for storing heat and an attenuation of dynamic fluctuations when the flash tank volume increases.

## 1 INTRODUCTION

Global warming is a serious problem for the planet caused by the development of human activities and industrial needs. Final energy consumption increased over the past few decades, reaching 160 PWh in the 2019 supply. More than 80 % of the energy supply comes from fossil fuels, which is the main reason for high emissions of $CO_2$ and GHG (Vaclav, 2017). The increased energy consumption of fuels based on carbon will be the primary cause of world $CO_2$ emissions in 2021, which are estimated to be 33 Gt (Newell, 2021). For industrial applications, the majority of the heat needed is generated and distributed using steam at the needed saturated temperature (Arpagaus, 2018).
The main objective of this study is to develop a highly efficient technology for steam generation valorizing the industrial waste heat and consuming decarbonised and low carbon electricity. These devices are heat pumps and mechanical vapour compression MVC. Heat pump integration is not regarded as a novel technology that has been suggested by the industry; on the contrary, heat pumps are among the most effective means of decarbonization (Abbasi, 2021), and their energy integration is widely used in a variety of industrial applications, particularly for high temperature heat supply. Comprehensive evaluations of the state of the art in industrial heat pump applications were published by Wolf (2017). Arpagaus (2018) conducted research on the need for heat below 200 °C in the European and global markets, as well as the possibility of producing this heat using heat pumps. Schlosser et al. (2020) research on large-scale heat pumps shown their potential for cost-effective installations and savings. Similarly, MVC is a known technology that is continuously developed in order to meet industry demand. A centrifugal water vapor compressor for HTHP with single-stage compression was designed by Madsboell et al. (2015) to meet industrial heating requirements (90–110 °C) and have a capacity ranging from 100 to 500 kW.


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A flash tank is a device used to connect different steam generation equipment, such as heat pumps and MVC. In the previous article (part 1) (Jouni, 2024), a dynamic model of a flash tank was developed in order to study its behaviour during fluctuations of sources and needs. The model was experimentally validated, and results show good tracking for water temperature and level in the flash tank with an error below 0,5 °C and 3 % respectively.
In this article, the objective is to study the flash tank capacity for storage at high temperatures and to investigate its robustness and flexibility while facing dynamic variations in sources and needs. The study, performed using the previously validated model, analyses the tank volume effect of flexibility.

## 2 SYSTEM DESCRIPTION

In our study, the system used for steam generation is a heat pump valorizing industrial waste heat, coupled to a flash tank, and the last one is connected to 2 MVCs supplying steam at the required pressure, as presented in figure 1. The study will be limited to constant electric and isentropic efficiencies for the system compressors with variable volumetric efficiency, as the main objective of this paper is to study the capacity of the flash tank to store heat in addition to its ability to bring flexibility and robustness to the system under dynamic variations of sources and needs.

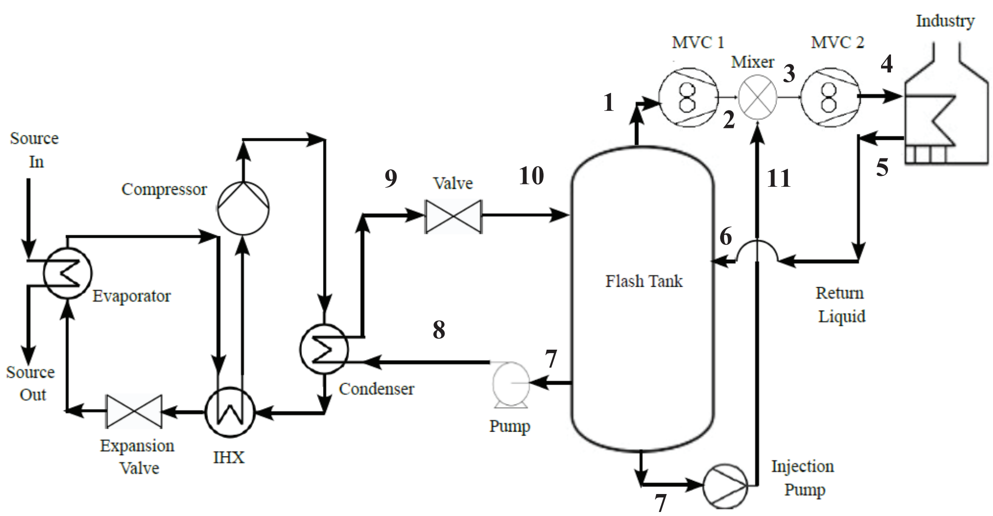


**Figure 1:** Steam Generation System

The heat pump uses R1336mzz(Z) as working fluid because of its high critical temperature and low pressure one: 171.3 °C and 29 bar (Jiang, 2022), which means low pressures in the heat pump circuit, in addition to its good environmental properties (low GWP and ODP = 0).
In the flash tank, saturated water is coupling the heat pump with the MVCs. It acts as a heat sink for the heat pump while serving as a vapour source for the MVCs. The circulating pump absorbs the saturated liquid from the flash tank and circulates it, at a higher pressure, through the heat pump condenser, it is heated to a higher temperature. Heated water is then flashed in the flash tank, where part of it is converted into steam and the rest remains liquid that will be recycled in the system.
The first MVC absorbs the saturated steam from the flash tank and increases its pressure, which leads to an increase in the saturation temperature. The outlet steam of the first MVC is superheated steam that should be cooled before entering the second MVC. An injection pump sucks an amount of the saturated liquid from the flash tank and injects it at the outlet of the first MVC in order to obtain saturated steam in the mixer that will be absorbed by the second MVC to increase its pressure to the needed one. Figure 2 shows the P-h diagram of water in the system.



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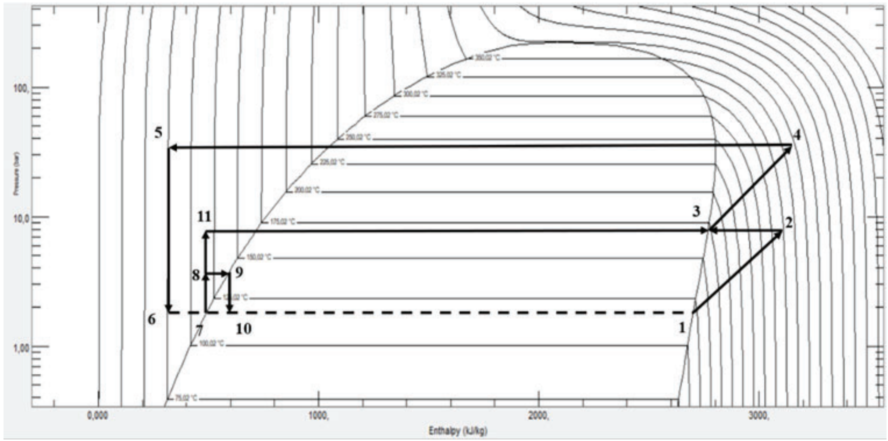


**Figure 2:** Water P-h Diagram in the System

**Table 1:** Water P-h Diagram Description

| Lines | Functions |
|---|---|
| 1 → 2 | MVC 1 |
| 2 → 3 & 11 → 3 | Mixer |
| 3 → 4 | MVC 2 |
| 4 → 5 | Steam use in industry |
| 5 → 6 | Returning condensates from process |
| 7 → 8 | Circulating Pump |
| 8 → 9 | Condenser Heat Pump |
| 9 → 10 | Flashing Fluid after the Condenser |
| 7 → 11 | Injection Pump |

## 3 MODELLING

The model of the flash tank was presented and validated in the part 1 paper (Jouni, 2024). For the heat pump and the MVC, a simplified model is used in the study. The heat pump compressor and the MVC will be modelled as a compressor with constant electric and isentropic efficiency and a variable volumetric efficiency based on the pressure ratio across the compressor.

The heat pump architecture considered in this study includes an internal heat exchanger (IHX). This IHX improves the COP by increasing the superheat at the compressor inlet while creating a large subcooling area before the expansion valve. The advantage of such an IHX depends on the refrigerant properties used (Besbes, 2015). The design of the IHX allows for optimisation of the COP of the heat pump by targeting a certain subcooling. The consequence is a superheated temperature at the compressor inlet that is related to the condenser outlet temperature and the IHX minimum temperature difference. Ensuring the safety of the compressor requires limiting the discharge temperature; therefore, this superheat should be controlled to avoid exceeding the acceptable discharge temperature limit.

Therefore, the inlet temperature of the compressor is defined based on the one at the outlet of the condenser and the minimum temperature difference of the IHX. If the outlet temperature of the compressor is higher than a predefined maximum, the one at the inlet of the compressor will be chosen in order to respect this criterion (this will mimic a partial bypass of the IHX that is usually used to protect the compressor). The heat pump in the system will be operated at full capacity. The equations used for the heat pump and MVC modelling are:


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$$\eta_{vol} = 1 - 0.05\ \frac{P_{cond}}{P_{evap}} \tag{1}$$

$$\dot{m}_{ref} = Nb_{pistons}\ \ V_{swept}\ \rho_{inlet,comp}\ \frac{RPM_{max}}{60}\ \ \eta_{vol} \tag{2}$$

$$T_{comp,in} = \ T_{cond,out}\ \text{-}\ Pinch_{IHX} \tag{3}$$

$$h_{comp,out} = \ \frac{h_{comp,out,isen} - h_{comp,in}}{\eta_{isen}} + h_{comp,in} \tag{4}$$

$$T_{comp,out} = \ f(P_{cond}, h_{comp,out}) \tag{5}$$

If $T_{comp,out} > T_{max}$, $T_{comp,out} = T_{max}$ & $T_{comp,in} = f^{-1}(T_{comp,out}, P_{cond}, P_{evap})$

If $T_{comp,out} > T_{max}$,

$$\dot{m}_{ref,new} = Nb_{pistons}\ \ V_{swept}\ \rho_{inlet,comp}\ \frac{RPM_{max}}{60}\ \ \eta_{vol} \tag{6}$$

$$W_{comp} = \ \frac{\dot{m}_{ref}\ (\ h_{comp,out} - h_{comp,in})}{\eta_{elec}} \tag{7}$$

$$W_{MVC} = \ \frac{\dot{m}_{vapor,in}\ (h_{mvc,out} - h_{mvc,in})}{\eta_{elec}} \tag{8}$$

$$W_{pump} = \ \frac{\Delta P\ V_{water}}{\eta_{pump}} = \frac{\Delta P\ \dot{m}_{water}}{\rho_{water}\ \eta_{pump}} \tag{9}$$

## 4 CASE STUDIES

The heat pump used in this study is a subcritical heat pump using R1336mzz(Z) as the working fluid. The global volume swept by the compressor for all the pistons is around 61.32 L per rotation. The electric and isentropic efficiencies are 0.9 and 0.7, respectively (Fricker, 2014). The maximum speed of the piston compressor is 1500 RPM, which limits the flow of refrigerant absorbed by the heat pump in addition to the volumetric efficiency mentioned in the previous section. The source of the heat pump will be the industrial waste heat, represented as water at 60 °C. Furthermore, a maximum temperature of 180 °C will be applied at the HP compressor's output to adhere to the compressor's threshold discharge temperature and prevent oil degradation.

For industrial and high temperature applications, the most MVC cited in the literature are double-screw and piston vapour compressors. In general, the maximum pressure ratio applied by one stage on these MVCs is around 3 (Shen et al., 2016; Hu, 2018). For the MVC, the electric and isentropic efficiencies are 0.7 and 0.95, respectively. The needed steam should have a saturated temperature of 200 °C, equivalent to 15.55 bar, with a subcooled condensate returned to the flash tank at 90 °C. Since each MVC has a maximum pressure ratio of 3, the minimum flash tank pressure should be 1.73 bar, equivalent to 116 °C, in order to let the MVC absorb the needed amount of vapour and increase its pressure to the needed one. The storage limitation will be reached when the flash tank temperature reaches 116 °C. The injection and circulating pump will have an efficiency of 0.5, taking into account the hydraulic, mechanical, and electric efficiencies, and the maximum flow that passes through the circulating pump is fixed at 100 $m^3$/h.

Different scenarios will be investigated in this paper in order to study the flexibility provided by the flash tank and its ability and capacity for heat storage while observing dynamic fluctuations of the sources and needs with respect to its volume and the level of liquid water. The scenario will be divided into two main sections in order to study the effect of each variation on the flash tank: steam demand variations and waste heat variations.



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For each case study, the volume of liquid water present in the flash tank is varied between 2 and 13 m$^3$, considering 80% of the global flash tank volume.

### 4.1 Steam Demand Variations

In this section, we will study the effect of the steam demand variation on the flash tank dynamic behavior and system performance. The variation will be sinusoidal for 2 hours between 2.5 and 1.5 t/h of steam at a saturated temperature of 200 °C, as presented in figure 3. In this case, the source flow (waste heat) will be assumed to be fixed at 100 m$^3$/h. The simulations will start with an initial flash tank temperature of 132 °C.

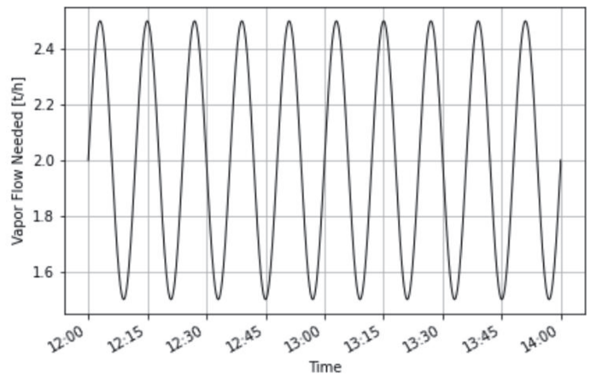


**Figure 3:** Profile of Steam Demand

The results show that the system tries to find an equilibrium between the steam demand and the steam generated by the heat pump. The flash tank temperature is stabilised at an average of 132 °C. The amplitudes and variations around 132 °C are functions of the water volume in the flash tank. The more water volume is increased, the lower the amplitude around 132 °C, as presented in figure 4.

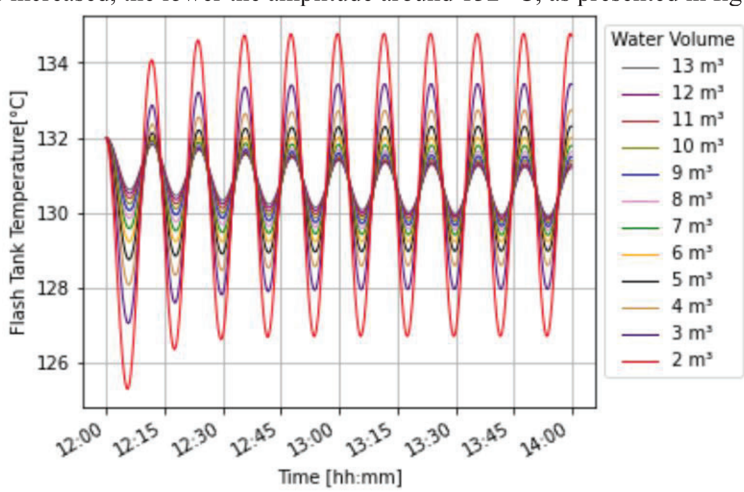


**Figure 4:** Flash Tank Temperature Variation

With the decrease in water volume, we will get more fluctuations in the flash tank temperature, which will slightly affect the heat pump and the MVCs performance and increase the energy consumed by the system. Figure 5a presents the global system COP variation with respect to time, with a slight difference in the system efficiency when the water volume in the flash tank varies. The increase in energy consumed by the system when the volume is varied from 13 to 2 m$^3$ is, however, very low (<0.5%), as shown in figure 5b.


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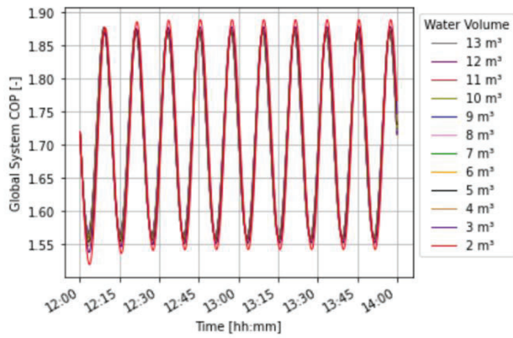


**Figure 5a:** Global System COP

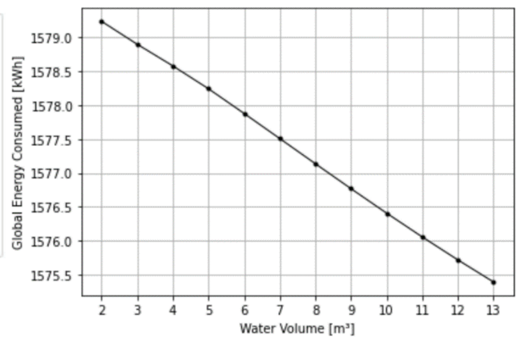


**Figure 5b:** Energy Consumption

**Figure 5:** COP and Energy Consumption

Let's take the case of a water volume of 7 $\mathrm{m}^3$ to understand the electric consumption distribution between the different components in the system. Figure 6 presents the distribution of the electric consumption between the heat pump compressor $\mathrm{W}_{\mathrm{comp}}$, the two MVCs $\mathrm{W}_{\mathrm{mvc1}}$ & $\mathrm{W}_{\mathrm{mvc2}}$, the injection $\mathrm{W}_{\mathrm{pump,inj}}$ and the circulating $\mathrm{W}_{\mathrm{pump,cir}}$ pumps, in addition to the global electric consumption $\mathrm{W}_{\mathrm{elec,total}}$. As shown in this figure, most of the electric consumption comes from the heat pump, then the 2 MVCs. The injection and circulating pumps present negligible electric consumption compared to the one absorbed by the system compressors.

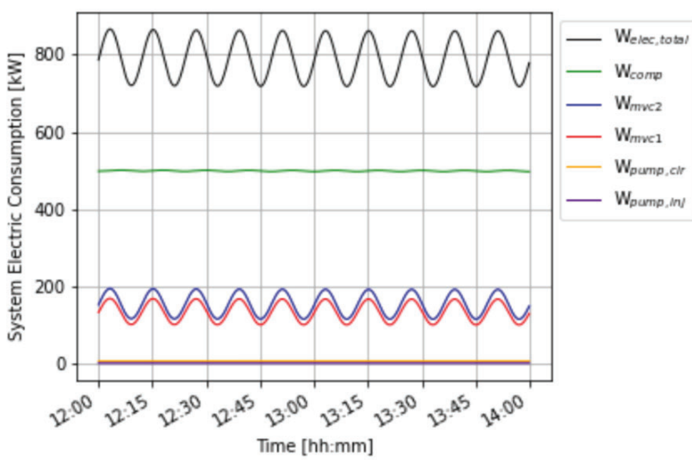


**Figure 6:** System Electric Consumption for $\mathrm{V}_{\mathrm{water}}$ = 7 $\mathrm{m}^3$

### 4.2 Storage Capacity under Demand Change

The previous section showed the capacity of the flash tank to stabilize the performance of the heat pump system when demand is varying in a periodic way.

In this section, we evaluate the capacity of the flash tank to store energy in order to overcome a temporary increase in steam demand.

For this scenario, we start at a flash tank temperature of 130 °C and a steam demand fixed at 2 t/h. For the whole scenario, the heat source flow is 100 $\mathrm{m}^3$/h. We apply a sudden steam demand increase, and we calculate the time needed to reach the minimum acceptable pressure in the tank to produce saturated steam at 200 °C, which is 1.73 bar equivalent to 116 °C. The storage capacity is studied for an increase to 2.5 and 3 t/h when the system is designed to generate 2 t/h of steam at an equilibrium temperature of 130 °C.


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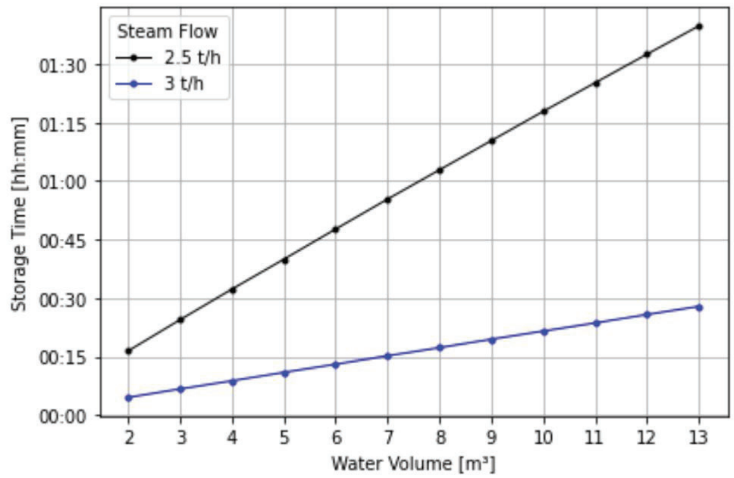


**Figure 7:** Storage Time

The storage time, as presented in figure 7, for the generation of 2.5 t/h of saturated steam at 200 °C varies between 24 minutes for 2 $m^3$ of water to 1 hour and 40 minutes for 13 $m^3$. For 3 t/h of steam, the storage time is much lower and varies between 4 minutes and around 30 minutes for 13 $m^3$. These results show that the flash tank is a good piece of equipment for flexibility and storage when demand varies.

### 4.3 Heat Source Variation

In this section, the effect of heat source variation will be investigated with a fixed demand of 2 t/h of steam at a saturated temperature of 200 °C. The heat source temperature will be fixed at 60 °C, and its flow will have a sinusoidal variation between 80 and 120 $m^3$/h, as shown in figure 8.

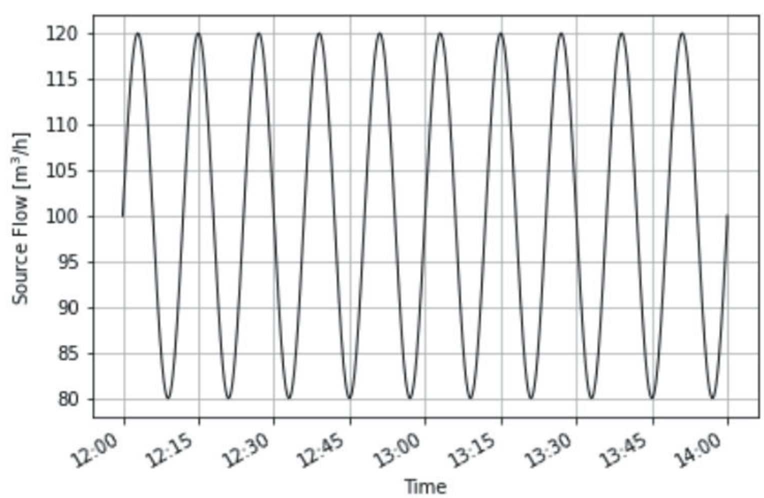


**Figure 8:** Mass Flow Variation of Heat Source

As for the scenario of demand variation, the system tries to stabilize the flash tank temperature at an equilibrium temperature of around 130.5 °C. Further, the water volume increase leads to a reduction of the temperature variation amplitude around 130.5 °C, as presented in figure 9.


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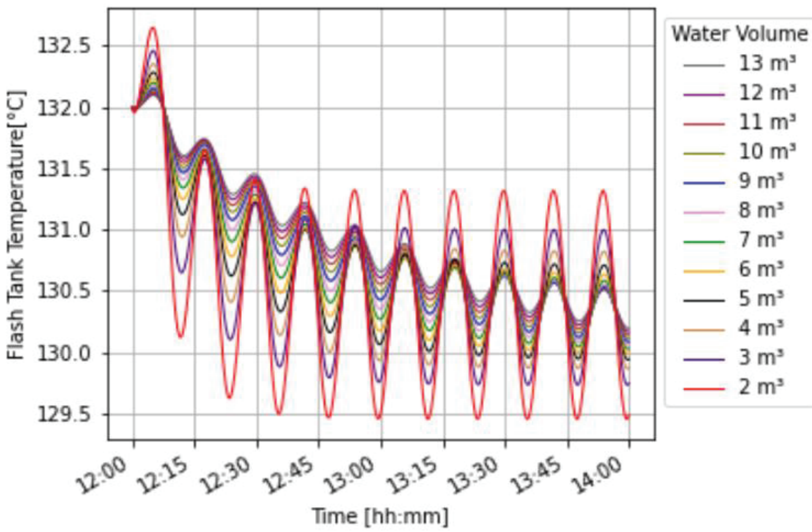


**Figure 9:** Flash Tank Temperature Variation

In addition, here also, increasing the water volume in the flash tank will slightly affect the global COP and energy consumption of the system, with an increase of less than 0.5 % for the energy consumed when we lower the water volume from 13 to 2 $m^3$, as shown in figures 10a and 10b.

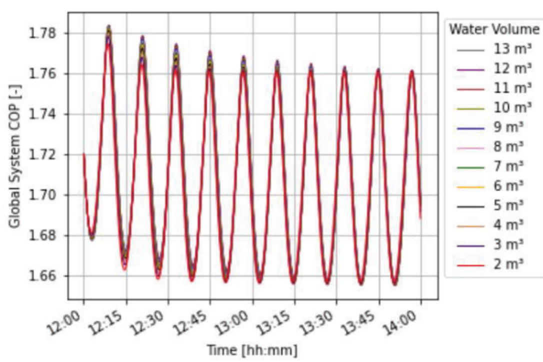


**Figure 10a:** Global System COP

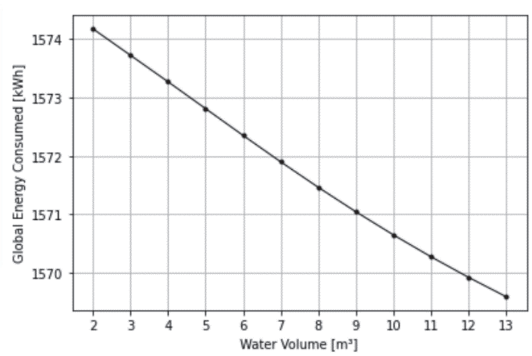


**Figure 10b:** Energy Consumption

**Figure 10:** COP and Energy Consumption

Let's try to integrate a storage system on the heat source side in order to maintain the flow at 100 $m^3$/h at the heat pump evaporator. The integration of the 1.4 $m^3$ storage tank at the source side will lead to a constant temperature in the flash tank.

Stabilizing the heat source flow rate leads to average performance, while varying the source flowrate allows to favour the heat pump when the flow is high and when it is low, it reduces its performance. However, these changes are not linear or symmetrical.

Indeed, figure 11 presents the energy consumption difference with and without heat storage integration on the source side. The energy consumed increases when the storage is added on the source side, showing this nonlinearity impact; however, this difference is very low.



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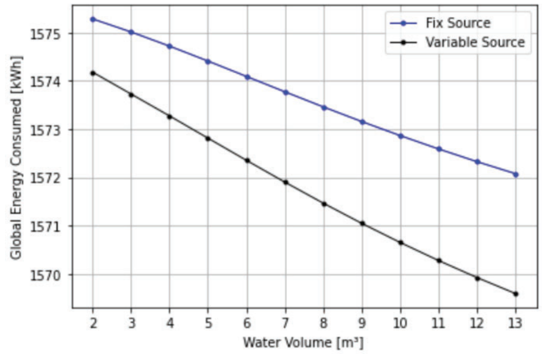


**Figure 11:** Energy Consumption Difference

### 4.4 Storage Capacity under Heat Source Change

In this section, we study the flash tank storage capacity while reducing the source flow, therefore, we start from the equilibrium flash tank temperature of 130 °C, the system will operate until 116 °C which is the lowest limit. While the source flow suddenly decreases to 80 and 60 $m^3$/h and remains constant at these values, the system could also stabilize its temperature above 116 °C, which means that the system could permanently work under these conditions, but the flash tank temperature will decrease to 126 and 118 °C respectively, as shown in figures 12. This new equilibrium is reached because the MVC is able to compensate the impact.

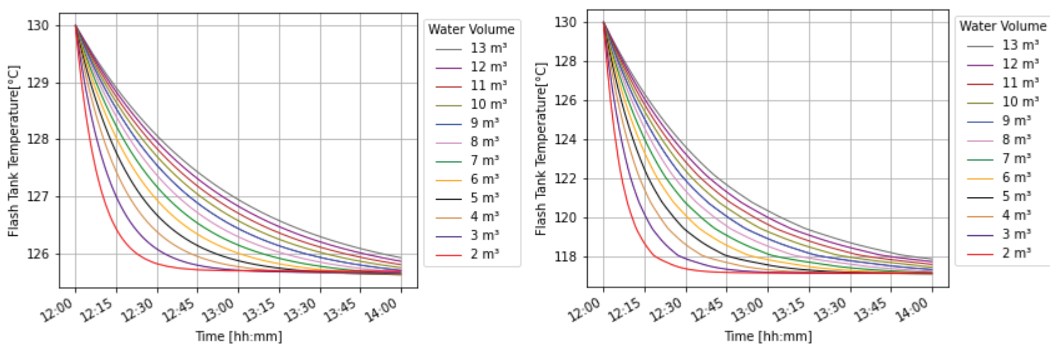


**Figure 12a:** Source Flow at 80 $m^3$/h **Figure 12b:** Source Flow at 60 $m^3$

**Figure 12:** Flash Tank Temperature Variation

The energy consumption for these two cases is presented in figure 13, where the energy consumption variation at 80 $m^3$/h is around 1 % compared to 3% for 60 $m^3$/h.

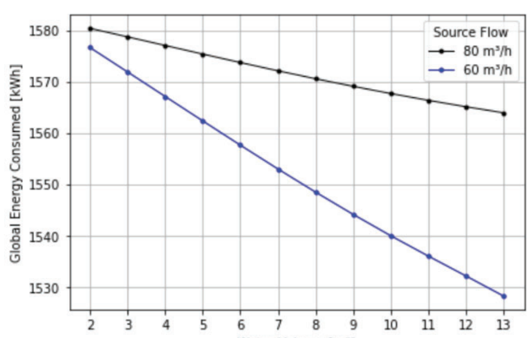


**Figure 13:** Energy consumption change


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While reducing the flow to 50 and 40 $m^3$/h, the system reaches 116 °C in the flash tank and stops steam generation at 200 °C. The storage time varies between 5 to 35 minutes for 50 $m^3$/h of flow with respect to the water volume, and 1 to 10 minutes for 40 $m^3$/h, as presented in figure 14.

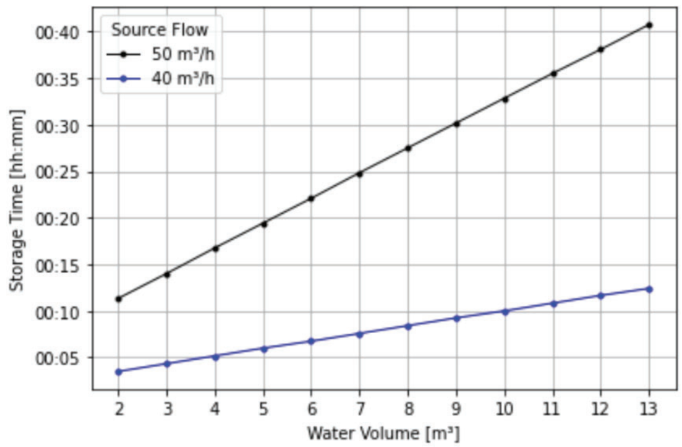


**Figure 14:** Storage Time

## 5 CONCLUSION

Steam generation is an important utility in industry. In this article, we want to generate steam at 200 °C and 15.5 bar using a high efficiency thermodynamical system valorizing the industrial waste heat while consuming low carbon electricity in order to contribute to industry decarbonization. The architecture presented in this study is the integration of a heat pump valorizing the waste heat represented by water at 60 °C and coupled to a flash tank, which is connected to two MVCs that absorb the low-pressure steam in the flash tank and compress it to reach 15.5 bar and 200 °C as saturation temperature. The flash tank model was defined and experimentally validated in a previous article, where a dynamic model of a flash tank was presented (taking into consideration mass conservation and energy balance equations) and validated using a dedicated test bench. The heat pump and MVC are represented as a simplified model, with a variable volumetric efficiency for the heat pump and constant electric and isentropic efficiencies for both equipment. Our objective is to evaluate the capacity of the flash tank to store energy at high temperatures, as well as its robustness and flexibility when facing dynamic variations in sources and needs based on its volume.

Results show a high flexibility for the flash tank while needs variations between 1.5 and 2.5 t/h of steam, where the flash tank temperature fluctuates around an equilibrium temperature with an amplitude that depends on the water volume present in the flash tank.

For the storing capacity, the flash tank shows a good storing time for around 1 hour and 40 minutes when we have 13 $m^3$ of water when the steam demand increases from 2 t/h to 2.5 t/h of saturated steam at 200 °C and around 30 minutes for 3 t/h of steam. This time changes based on the water volume and the amount of steam generated above its equilibrium point.

For the source variation of flow between 80 and 120 $m^3$/h, the results are similar.

When the source flow is decreased to 80 and 60 $m^3$/h, the system is also able to adapt above the minimum acceptable flash tank temperature which is 116 °C for steam generation at 200 °C using 2 MVCs. The new equilibrium at 80 and 60 $m^3$/h is 126 and 118 °C respectively.

For 50 and 40 $m^3$/h, the flash tank temperature will decrease below 116 °C and it took around 35 minutes for 13 $m^3$ at 50 $m^3$/h, and 10 minutes at 40 $m^3$/h.

Finally, we could say that a flash tank is an important solution for the system as a coupling device between two different equipment such as a heat pump and MVC, in addition to its high flexibility and robustness when facing dynamic variation in sources and needs, as well as its capacity for heat storage.



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## NOMENCLATURE

| | | |
|---|---|---|
| GHG | Green House Gas | |
| GWP | Global Warming Potential | |
| HTHP | High Temperature Heat Pump | |
| IHX | Internal Heat Exchanger | |
| MVC | Mechanical Vapour Compression | |
| ODP | Ozone Depleting Potential | |
| RPM | Round Per Minute | |
| $h$ | Enthalpy | (kJ/kg) |
| $m$ | Mass | (kg) |
| $\dot{m}$ | Mass Flow | (kg/s) |
| $P$ | Pressure | (Pa) |
| $Q$ | Heat | (kW) |
| $T$ | Temperature | (°C) |
| $t$ | Time | (s) |
| $u$ | Internal Energy | (kJ/kg) |
| $V$ | Volume | ($m^3$) |
| $\dot{V}$ | Volumetric Flow Rate | ($m^3$/s) |
| $W$ | Work | (kW) |
| $\eta$ | Efficiency | (-) |
| $\rho$ | Density | (kg/$m^3$) |

**Subscript**

| | |
|---|---|
| comp | Compressor |
| cond | Condenser |
| elec | Electric |
| evap | Evaporator |
| isen | Isentropic |
| mvc | Mechanical Vapor Compression |
| ref | Refrigerant |
| vol | Volumetric |

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