THEORETICAL AND EXPERIMENTAL STUDY OF FLASH TANK IN A HEAT PUMP BASED STEAM GENERATION – PART 1

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ABSTRACT

Heat pumps are technical options for increasing the energy efficiency of systems when used for waste heat recovery. They allow upgrading the waste heat by delivering it at higher temperatures while consuming decarbonised and low-carbon electricity. When it comes to generating steam at high temperatures, other equipment could be connected to heat pumps to obtain higher steam pressures and temperatures, such as water vapour compressors (MVC). The flash tank is considered a coupling device between the heat pump and the MVC, giving the system the advantage of coupling and flexibility, especially when dynamic variations of the steam demand occur. In this paper, a theoretical dynamic model of a flash tank connected to a heat pump has been developed in order to simulate steam generation and study the performance and behaviour of the flash tank in the case of dynamic variation of temperature and needs. A theoretical model was created, taking into consideration mass conservation and energy balance equations, in order to represent the transient behaviour. An experimental rig is built and used to validate the model on both steady state and dynamic behaviour. Results show a good tracking of water temperature and level in the flash tank, with an error of around 0,5 °C for the temperature and less than 3% for the water level. Moreover, the model predicts the amount of steam generated in this experiment.

1 INTRODUCTION

In order to control global warming and reduce the large amount of CO_2 and GHG emissions that reached around 33 Gt in 2021 (Nawell, 2021), mainly because of the high energy consumption based on fossil fuels and coal sources, different countries started to cut down their dependence on fuel-based equipment and replace it with electric devices that use decarbonised and low-carbon electricity in order to decarbonise their energy production and to respect the different international environmental regulations such as COP21 (Conference Of Parties 21, 2015 United Nations climate change conference, Paris, France).

Industry is one of the most energy-consuming sectors and accounts for more than 30% of CO_2 and GHG emissions (Ritchie, 2020). That's why, in order to respond to environmental regulations, decarbonisation and energy savings in the industrial sector must be an urgent task and a main focus. In many industrial fields, the production of hot water and steam is the main method for heat generation and a medium for heat exchange. In the Swiss industry, process heat accounts for about 54% of the total heat demand (84.9 PJ of 156 PJ in 2015) (Kirchner et al., 2008). For German industries, process heat, space heating, and hot water production consumed around 1 909 PJ in 2012, which corresponds to around 74 % of the total industrial heat demand of 2 578 PJ (Wolf et al., 2014; Wolf et al., 2012). In France, the heating processes in 2009 were estimated to be 119 PJ for temperatures between 60 and 140 °C (Chamoun et al., 2012; Dupont, 2009). For the USA, the graph shows that the heat demand between 40 and 200 °C is around 3 416 PJ (Fox, 2011). Nellissen et al. (2015) estimated a technical potential of

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626 PJ (174 TWh) for the European heat pump market at temperatures up to 150 °C. The majority of the heat needed is produced using steam at different pressures and temperatures (Arpagaus et al., 2018). Therefore, energy-saving technology for steam production will significantly reduce the amount of energy consumed by industry.

In order to generate steam, the most widely used method is fuel or gas boilers. To electrify these equipments, the idea is to connect a heat pump to a flash tank for steam generation, where a circulating pump absorbs the saturated liquid from the flash tank and circulates it through the heat pump condenser to heat it, then flashes it in the flash tank, where part of the flashed flow is converted into steam and the other part stays in liquid form to be recycled. Commercial heat pumps allow to supply heat up to 100 °C from waste heat sources (Chamoun et al., 2014), and several other heat pumps that are currently being developed can reach higher temperatures, such as Kobelco SGH120, which developed new heat pumps with a maximum temperature of 120 °C (Arpagaus et al., 2018), and Li et al. (2019), which developed a water-source cascade HTHP that can generate hot water temperatures of up to 170 °C using BY36/BY6 as refrigerants for industrial applications at high temperatures.

Kang et al. (2019) studied experimentally the performance of a steam generation heat pump with an internal heat exchanger connected to a flash tank and attempted to improve the steam production rate over the conventional industrial steam boiler. Bless et al. (2017) analysed theoretically the steam generation methods using heat pumps connected to different sources of energy, such as gas-fired boilers, electric resistance, and the direct usage of industrial waste energy using heat exchangers. Zhao et al. (2021) developed a theoretical model of a steam production heat pump coupled to a flash tank using industrial fatal heat and built a test bench in order to validate the simulated results and evaluate the system performance. In addition, steam compressors have been developed for decades (Holcroft,1965). Coupled with a flash tank, they can supply steam at low pressure (~5-7 bars), which is the typical pressure used in many processes. This coupling allows the combination of many heat sources (valorized by a lower temperature heat pump, directly recovered heat…) and flexibility since it procures a certain amount of energy storage.

This paper aims to analyse thermodynamic steam generation, explore the behaviour of the flash tank with dynamic variation at the source and the needs, study its flexibility for steam generation by developing a dynamic model on Python using TILMedia as a library for thermodynamic properties, and then verify experimentally the model by carrying out tests in the EDF laboratory. The flash tank will be connected to a heat pump or any source of energy, and then different tests will be realised in order to inquire about the variation of the water level in the flash tank and its saturation pressure and temperature.

2 SYSTEM DESCRIPTION

2.1 Test Bench

The flash tank used in our study is a part of the European project BAMBOO funded by the European Union under the Research and Innovation Horizon 2020 program for steam generation using a water-water high temperature heat pump HeatBooster HBS4 manufactured by Viking Heat Engines, connected to a flash tank unit for steam generation, as presented in figure 1, and the tests were realized at EDF Lab Les Renardières, in France.

Figure 1: Test Bench in EDF Laboratory

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In this paper, we will be modelling the flash tank, and we will study its behaviour under several dynamic fluctuations in needs and sources and inquire about the flexibility it provides for steam generation at different ranges of temperatures.

2.2 Flash Tank

The flash tank unit had been developed specifically for the HTHP and used for both testing in the lab and, subsequently, demonstration operations in semi-industrial scenarios. It is possible to generate saturated steam with this unit up to around 5 bar, equivalent to 152 °C.

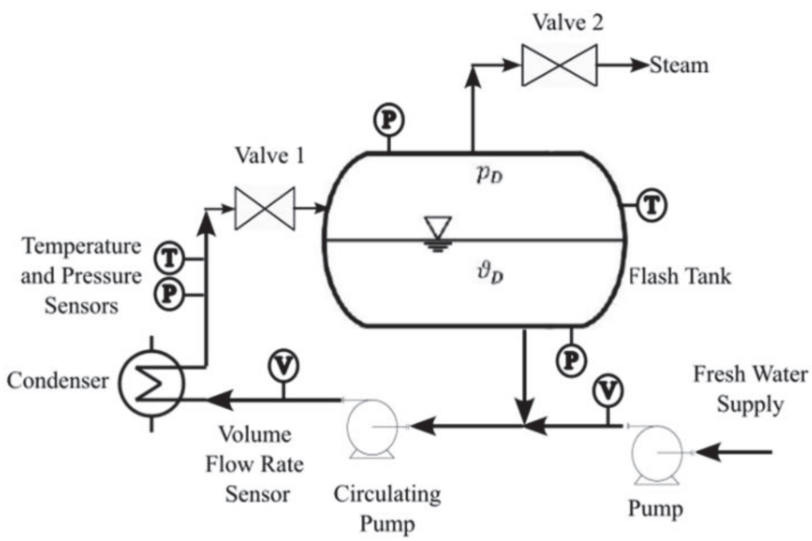

Figure 2: Schematic Representation of the Experimental Flash Tank with the Sensors

The flash tank used in our study is presented in figure 2 with all the connected sensors in order to identify the behaviour of the tank at each time step. In the flash tank, we have a temperature sensor and two pressure sensors at the top and bottom of the drum. These two sensors are used to determine the water level in the tank based on the pressure difference between them. Two volume flow meters are installed at the outlet of the pumps to define the flow rate at each point of the system. The first pump is used to supply the tank with fresh water while the water level in the tank decreases, and the circulating pump aims to pass the flow from the saturated liquid in the flash tank and the fresh water supplied in the condenser to be heated. Temperature and pressure sensors are connected at the outlet of the condenser in order to define the state of the returning flow to the flash tank. There is no flow meter for the steam leaving the tank, and in the next part of this paper, we will define the method used to estimate and calculate the exact amount of steam leaving the tank.
The sensors have the following precision:

- PT100 Temperature sensors: DIN EN 60751 – Class A: ± (0.1 + 0.0017 |t|) °C
- Pressure sensors for hot water: ± 0.5 % on measured value
- Pressure sensors for steam: ± 0.1 % on measured value
- Volume flow rate sensor: ± 0.5 % on measured value (electromagnetic flow meter)
- Power measurements: ± 1% on measured value (three-phase current meter)

3 MODELLING

In order to simply the modelling of the flash tank, it will be considered as a cylinder connected to an ellipsoid, as presented in figure 3.

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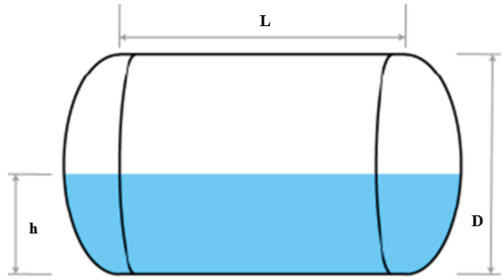

Figure 3: Flash Tank Simplified Geometry

The cylinder part of the tank has a length of 1,5 m and a diameter of 0,7 m. The ellipsoid has two semi-axes equal to 0,35 m and the third one of 0,141 m. It is made of steel with a thickness of 10 mm and insulated with glass fiber with a thickness of 20 mm.

Table 1: Flash Tank Properties

Cylinder Part	**Length - L**	1,5 m
	Diameter - D	0,7 m
Ellipsoid Part	**Semi-axe 1 - R**	0,35 m
	Semi-axe 2 – R	0,35 m
	Semi-axe – G	0,141 m
Material	**Steel**	0,01 m
Isolation	**Glass Fiber**	0,02 m

By calculating analytically the volume of the tank, we obtain a relation between the water level in the tank and the volume of water presented in the drum, where h is the water level in the tank:

$$V = \frac{2}{3}\pi\, G\, R^2 - G\frac{\pi}{R}[R^2(R - h) - \frac{(R-h)^3}{3}] + \frac{1}{2}R^2(\alpha - sin(\alpha))L \; ; \; with\ \alpha = 2cos^{-1}(\frac{R-h}{R}) \quad (1)$$

For the dynamic study, we will assume that the flash tank is an open system; therefore, two equations are needed to model the system: The first one is for the mass balance, and the second one is for the energy balance:

$$\frac{dm}{dt} = \Sigma\dot{m}_{in} - \Sigma\dot{m}_{out} \quad (2)$$

$$\frac{dU}{dt} = W + Q + \Sigma\dot{m}_{in}\, h_{in} - \Sigma\dot{m}_{out}\, h_{out} \quad (3)$$

$$\frac{(m_{water,FT} + dm)\, u_2 - m_{water,FT}\, u_1}{dt} = \Sigma\dot{m}_{in}\, h_{in} - \Sigma\dot{m}_{out}\, h_{out} - Q_{Losses} \quad (4)$$

For the energy balance, there is no work W done in the tank, and Q_{Losses} represents the energy losses due to the ambience (eq. 4). The heat inertia presented in the flash tank wall is also considered. The equations used to model Q_{Losses} and metal inertia are:

$$Q_{Losses} = hc_{FT,wall}\, A_{in}\, (T_{FT} - T_{wall}) \quad (5)$$

$$m_{wall}\, Cp_{wall}\, \frac{T_{wall,new} - T_{wall}}{dt} = hc_{FT,wall}\, A_{in}\, (T_{FT} - T_{wall}) + hc_{isol,atm}\, A_{out}\, (T_{amb} - T_{wall}) \quad (6)$$

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In our model, we assume that the wall thickness is thermally negligible and that the wall has a uniform temperature along its thickness.
The three main equations for mass balance, energy balance, and metal inertia are used to model the system and to calculate the flash tank temperature at each time step. The new flash tank temperature is identified based on the new drum density and internal energy calculated using these three equations. On the other hand, the relationship between volume and water level is used in order to also define the level of water at each time step.

4 STEAM FLOW RATE CALCULATION

The bench test had been developed in order to generate steam at a specific temperature T_{Needed} defined by the user. The steam control valve opens in two cases: First, it opens when the flash tank temperature is below 100 °C in order to eliminate all the air present in the tank to avoid the presence of air in the tank, then it closes to increase the drum pressure. Further, it opens when the flash tank temperature is higher than the needed temperature T_{Needed}, therefore, the steam produced is evacuated out of the tank in order to maintain its temperature at a value as defined by the user. Thus, the modelling will be divided into two main sections:

- First section, when the flash tank temperature T_{FT} is below the needed one T_{Needed}, there is no steam leaving the tank, and the temperature is calculated based on the model by considering the steam flow at 0.
- For the second section, the strategy used for steam calculation is the 'Temperature Tracking Method'. In this method, the measured temperature of the flash tank is used as an input to the model. It is used in order to calculate the internal energy, and while applying the energy balance, the steam flow can be calculated. At the end of the test, we obtain the steam flow rate leaving the tank without the need for the required sensor.

In order to validate the model, for the first section, the temperature and pressure measured will be compared to the model outputs. As for the second section, we will compare the water level calculated to the water level obtained by the flash tank sensors.

5 EXPERIMENTS DESCRIPTION

The experiment used to confirm the model is divided into different sections in order to validate different modes in the flash tank. The experiment starts at 11:00 AM:

- Section 1: The flash tank temperature is 20°C equal to room temperature. Our objective is to heat the flash tank using the heat pump until it reaches a temperature of 115 °C and starts to generate steam at this temperature. We tried to validate the dynamic model of the flash tank in this section, which took around 1 hour and 22 minutes to be achieved.
- Section 2: We try to stabilize the flash tank temperature at 115 °C by evacuating the steam generated by the heat pump. Here, we tried to validate the flash tank model in a static mode where its temperature remains constant and the valve opens to evacuate the excess steam. This section took around 10 minutes.
- Section 3: The heat pump is stopped, and the valve is completely opened in order to obtain an atmospheric pressure in the flash tank. A large amount of steam is crashed out of the drum, and the flash tank pressure and temperature decrease until reaching 1 bar and a temperature of 100 °C. In this part, we aim to study the thermal insulation of the flash tank. This part of the study lasts around 2 hours.
- Section 4: The objective is to heat the flash tank in order to produce steam at 145 °C; therefore, the temperature will increase from 95 °C to 145 °C using the heat pump. Here, we also tried to validate the dynamic model of the flash tank, but at different ranges of temperature, and it took around an hour.

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- Section 5: The objective is to stabilize the flash tank temperature at 145 °C in order to study the static mode at the flash tank at higher temperatures and then to present the ability to produce steam at high temperatures.

6 EXPERIMENTAL VALIDATION

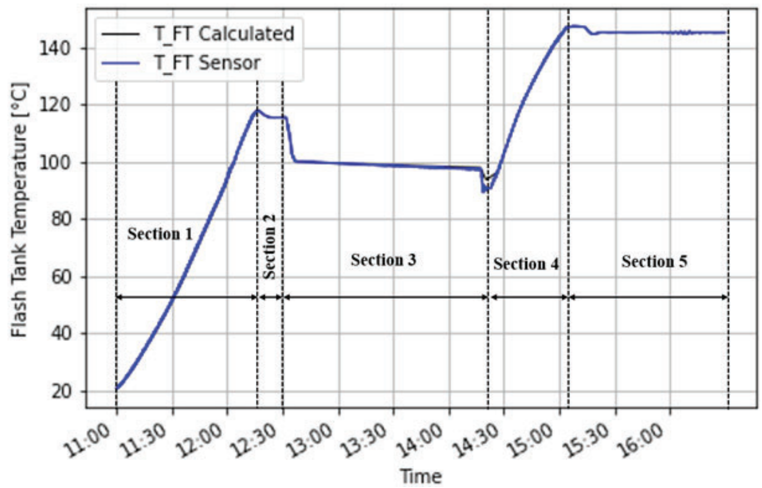

Figure 4: Flash Tank Temperature

Figure 4 shows the temperature of the flash tank during the experience, where the model prediction is good with a negligible difference between the calculated and measured temperature in the different modes tested while making the experiment.

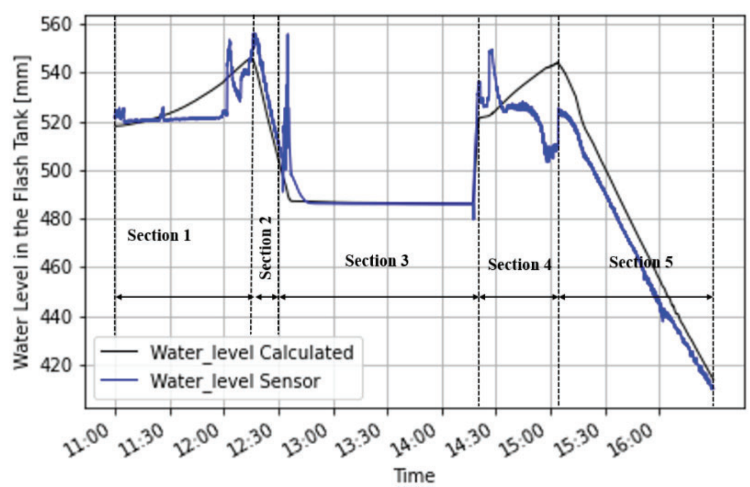

Figure 5: Water Level

The calculated water level, as shown in figure 5, agrees with the water level determined by the sensor, despite some noise in the measured values. In section 1, water heating leads to a density change and, therefore, a water level increase. The same phenomenon occurs in section 4. For both sections, the measured value is noisy. In sections 2 and 5, the model predicts well the water level variation due to the steam rejection. This allowed us to derive the steam mass flowrate, as shown in figure 6.

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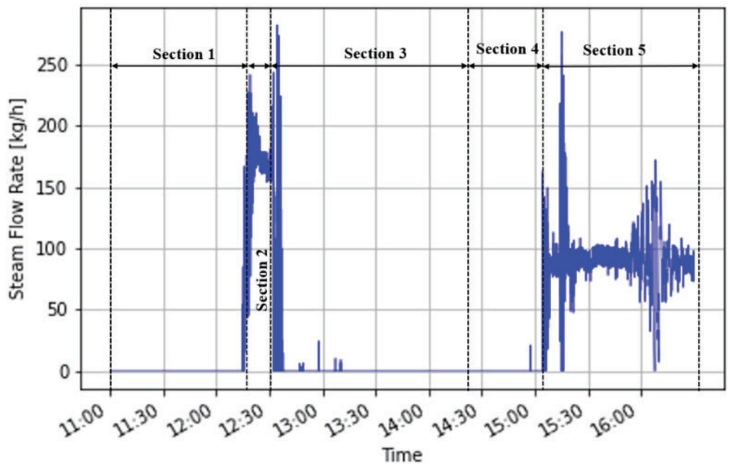

Figure 6: Steam Flow Rate Calculated

6.1 Transition Sections

In sections 1 and 4, the objective is to increase the flash tank to 115 °C and 145 °C respectively. There is no steam flow out of the tank in these two sections because the valve is closed. The flash tank temperature and water level were calculated by the model and then compared to the data obtained by the sensors. In section 1, the average error of the temperature difference is around 0,63 °C and the percentage error for water level is less than 1%. For the section 4, the error for the temperature is 0,5 °C.

6.2 Static Sections with Steam Generation

In sections 2 and 5, the target was to stabilize the flash tank temperature at 115 °C and 145 °C respectively. The steam flow out of the tank in these sections isn't obtained by sensors, so the temperature tracking method was used in order to calculate the water level and the steam flow generated. The average production of saturated steam at 115 °C in section 2 is around 160 kg/h, equivalent to around 100 kW, and 90 kg/h of saturated steam at 145 °C equivalent to 53 kW in section 5. There is no error in the temperature because of the temperature tracking method used in this section. The percentages of error for water level are around 1.6 % and 2 % for sections 2 and 5, respectively.

6.3. Static Section with no Steam Generation

In section 3, we only studied the heat losses to the ambiance and the flash tank insulation. At the beginning of this section, we have an amount of steam produced because the valve was open in order to reduce the flash tank temperature from 115 to 100 °C. This sudden opening of the valve causes the steam flow until stabilizing the flash temperature at 100 °C. The water temperature and level were calculated and compared to the results obtained by the sensors, which show an error of 0,5 °C for the temperature difference and 0.46 % for the water level.

7 CONCLUSION

The development of the industry increases the potential to consume fossil fuels in order to respond to their needs, which leads to increase CO_2 and GHG emissions that contribute to global warming. The solution is to start decarbonizing the industry and electrify their heat needs using high efficiency technologies that use decarbonised electricity in order to convert it into heat.

A new technology had been studied in order to electrify steam production using a flash tank connected to a high temperature heat pump. A dynamic model was developed in order to study the flash tank behaviour with fluctuation of needs and sources. The system was modelled on Python, using TILMedia as a library of thermodynamic properties. The equations of mass balance, energy balance, and wall energy inertia used in the simulation were presented in the paper in order to model the flash tank. A

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new method was developed to estimate the missing value of the steam flow rate that leaves the flash tank because of the unavailability of the needed sensor. The dynamic model of the flash tank had been validated based on an experiment testing static and dynamic modes at different working temperatures. The model presents good tracking for the flash tank temperature and water level, which ensures the validity of the dynamic model and the feasibility of steam production using the flash tank technology, with a small error for water temperature and level in each sector.

NOMENCLATURE

FT	Flash Tank	
GHG	Green House Gas	
HTHP	High Temperature Heat Pump	
MVC	Mechanical Vapour Compression	
A	Area	(m^2)
Cp	Specific Heat	(kJ/kg/K)
h	Enthalpy	(kJ/kg)
hc	Heat Convection Coefficient	(kJ/kg)
m	Mass	(kg)
$\dot{m}$	Mass Flow	(kg/s)
Q	Heat	(kW)
T	Temperature	(°C)
t	Time	(s)
u	Internal Energy	(kJ/kg)
W	Work	(kW)

Subscript

FT	Flash Tank
amb	Ambient
isol	Isolation

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