System design and first operational experiences in a paper mill of a steam-generating Type II absorption heat pump

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Abstract

An Absorption Heat Transformer or Type II Absorption Heat Pump is a thermally driven heat pump that upgrades approximately half of its driving heat to a higher temperature level with almost negligible electric power consumption. Usually, such heat pumps recover waste heat from a renewable or waste heat source and upgrade it to a usable higher temperature. This work presents an integration scheme in which an upgraded hot water stream can be used with a flash tank to produce saturated steam for industrial processes.
The subsystem for steam generation (steam generation module or SGM) has been expanded with a Thermocompressor, which allows for steam supply at higher pressures, if a driving high-pressure steam flow is available in the plant. Following the presented integration scheme, an industrial pilot heat pump delivering about 350 kW of steam at 3.3 bar(a) by using waste heat at 90 ºC has been designed and installed in a paper mill in Italy as part of a European project. The absorption heat pump has been designed based on a previous smaller unit designed for waste heat upgrade in a refinery. The present design has been modified to minimize the risk of crystallization under operation with high delivery temperature and low cooling water temperature. The expected performance for the absorption heat pump is discussed with regards to the steam generation, when operated together with a flash tank and a Thermocompression. The first operational results confirm the soundness of the heat recovery concept and its stable operation in a real environment.

Keywords: absorption heat transformer ;high temperature heat pumps; steam

1. Introduction

Type II or booster absorption heat pumps are commonly referred to as absorption heat transformer (AHT). Such heat pumps are able to split a heat flow at an intermediate temperature level into two heat flows, one at a higher temperature level (upgraded heat flow) and another one at a lower temperature level (rejection heat flow). A thermal coefficient of performance of nearly 0.5 is a typical value.

Absorption Heat Transformers are ready-to-market delivering upgraded heat with temperatures up to 150 ºC with very small electric consumption compared with vapor compression heat pump. System electrical coefficients of performance in the range of 25-50 are normal and even higher values can be reached. Therefore, Absorption Heat Transformers are especially suitable for the recovery and upgrade of waste heat from industrial processes with small electricity consumption. Applications reported in the literature focus on the pulp and paper (during and lamination processes), chemical and petrochemical (distillation and purification processes) and food and beverage sectors (drying, sterilization, fermentation and mold and bacteria processes). Especially in the chemical and paper industry, steam is the most common heat carrier used for processes. For

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15th IEA Heat Pump Conference 2026 - HTH8.4 - https://doi.org/10.23697/r2e5-6a31

this reason, understanding and optimizing the integration of steam producing heat pumps is key for the introduction of such technologies.

Steam-generating heat pumps have progressed from concept to reality in the past decade. Mechanical compression heat pumps, with high recovery efficiencies using electrical input, are rapidly evolving to cover a supply of ~5 – 6 bar steam (~150 – 160 ºC) [1], and Type II absorption heat pumps, a thermally driven route are already applied in dozens of industrial projects. Each approach has its niche, but ongoing demonstration projects and accumulating operational experience are expected to improve confidence, drive costs down, and broaden the adoption of steam-generating heat pumps across industries worldwide. This paper presents a possible integration route for the delivery of steam with 6.5 bar using a Type II absorption heat pump.

2. Case and System Description

The steam-generating AHT is integrated in the steam production system of a paper mill in the Lazio Region, in Italy. The system, developed in the framework of the European PUSH2HEAT Project, has been designed, manufactured and installed in the facilities of Cartiere di Guarcino, a paper mill for the production of specialty papers. In the framework of this European project, the operation of the system will be monitored and optimized. The Cartiere di Guarcino paper mill consumes up to 15 ton/h of steam that are delivered at two main steam lines: one high pressure steam network with a pressure between 10 and 14 bar(a), and a middle pressure steam network with a pressure of 6.5 bar(a).

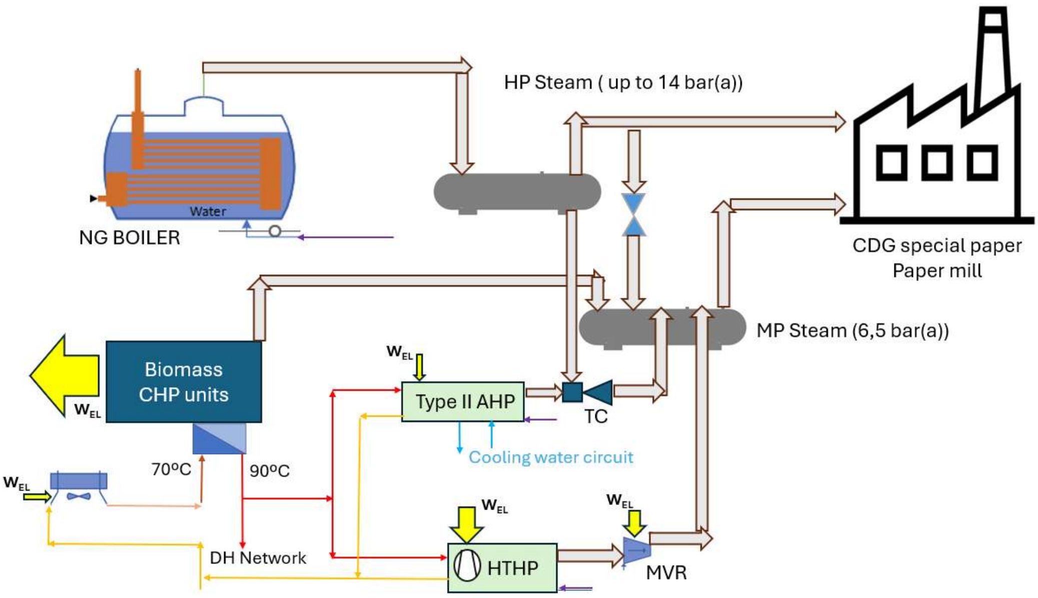

Fig. 1. Type II AHP integrated in the steam production system of a paper mill

As presented in Figure 1, steam with up to 14 bar(a) is delivered by a natural gas boiler, while steam at 6.5 bar(a) is delivered by a heat steam recovery generator of a biomass-based cogeneration plant. The cogeneration plant consists of 3 parallel motors. In addition to the generated power and steam, hot water with up to 90ºC is obtained from the cooling jacket of the cogeneration units. This heat was planned to be delivered to a district heating network, that is not operational nowadays and the heat must be released to the environment using cooling towers to return the water to the cooling jackets at the required temperature.

In the PUSH2HEAT project, this heat, currently released to the environment and wasted, will serve as the heat source for two heat upgrade systems: I) a vapor-compression High Temperature Heat Pump coupled to a mechanical vapor recompression system, and II) a steam producing AHT-system coupled to a Thermocompressor (TC).

The AHT will deliver pressurized hot water at 141.5ºC and saturated steam at 3.3 bar(a) in combination with a flash tank, as presented in Fig 2. The Thermocompressor will then use motive steam from the high-pressure network to upgrade the pressure of the steam from the AHT-Flash Tank system and deliver it at a pressure of 6.5 bar(a) (169 ºC) to the MP steam line. Using a Thermocompressor allows for controlling the temperature and pressure inside the flash tank which is connected to the AHT absorber outlet.

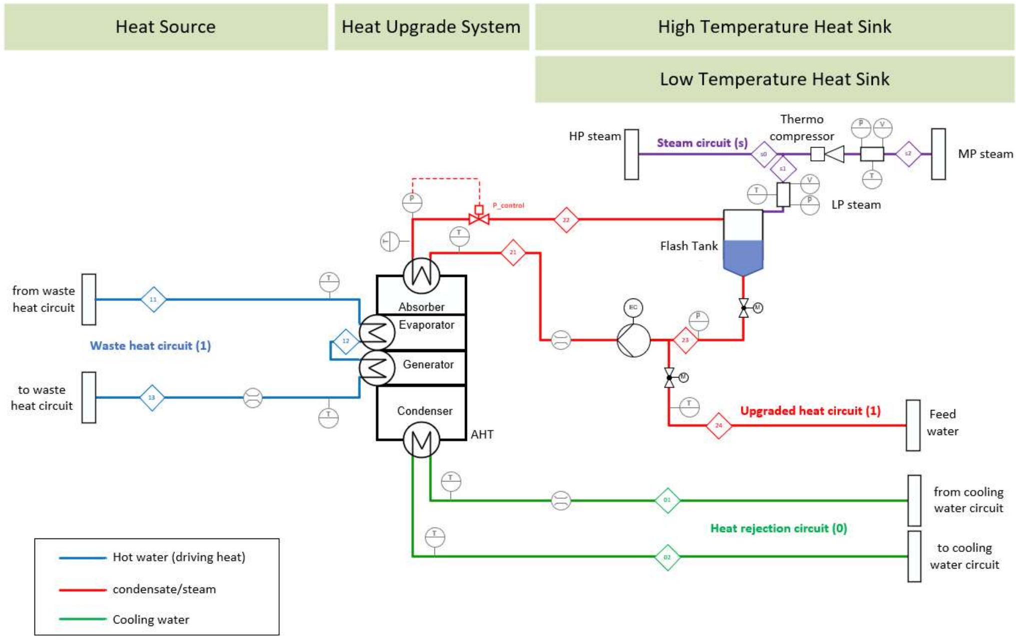

Fig. 2. System layout of the heat upgrade system consisting of an Absorption Heat Transformer (AHT), a Flash Tank (FT) and a Thermocompressor

Table 1 presents the design conditions for the operation of the AHT, the Flash Tank and the Thermocompressor. Driving heat and cooling water circuits temperatures are boundary conditions from the plant. The flow rates in these circuits have been fixed based on previous experiences on industrial applications of AHT and the recommendations from theoretical simulation studies [2]. The pressure of the steam produced at the Flash Tank has been chosen considering the ratios between the suction and motive steam pressures and flow rates, the plant demand and the expected performance of the AHT under given conditions.

Table 1. Operating conditions of the heat upgrade system for the monitored steady state points

Prototype	unit	Nominal	expected minimum	expected máximum
Flow rate V_A at upgraded heat circuit (Absorber-Flash Tank)	m^3/h	62.2	30	70
Flow rate V_{GE} at waste heat circuit (1) (E-H)	m^3/h	60	30	80
Flow rate V_C at heat rejection circuit T_0 (C)	m^3/h	38	20	80
Temperature at Condenser inlet, $T_{C,in}$	**ºC**	**15**	**12**	**25**
Temperature at Evaporator/ Generator inlet $T_{EG,in}$	**ºC**	**90**	**88**	**95**
Temperature at Absorber Inlet, $T_{A,in}$	ºC		136.5	
Temperature at Absorber Outlet, $T_{A,out}$	**ºC**	**141.5**	**139**	**150**
Gross Temperature Lift, GTL	**K**	**51.5**	**44**	**62**
Upgraded heat flow rate, $Q_{A,}$	kW	347	300	400
COP = Q_A / (Q_G + Q_E)		0.49	0.45	0.49
Steam from the Flash Tank @ 3,3 bar(a) (TC suction steam)	kg/h	540		
Motive steam from HP line @ 14,5 bar(a) (TC motive steam)	kg/h	2046	?	?
Delivered steam to MP line @ 6,5 bar(a) (TC outlet steam)	kg/h	2586	?	?

3. Absorption Heat Pump Type II (Absorption Heat Transformer, AHT)

3.1. Absorption Heat Pump requirement and internal design

The core element of the heat upgrade system is a single effect LiBr/H2O Type II Absorption Heat Pump or AHT manufactured by BS Nova (Baelz Group). This AHT, with a nominal capacity up to 500 kW is the third step in the development of a family of Type II absorption heat pumps. The performance of a first 40 kW prototype for variations in their working condition has been extensively reported in the 12th HPC Conference

[3]. The upscaling process for the development of the 200 kW industrial prototype has been presented in the 13th HPC Conference [4], together with the deviations observed between the expected performance and the results monitored in a real environment. The AHT presented in this work has been upscaled following a similar procedure, taking special care of the expected operating conditions for steam production, that result in large gross temperature lifts, with relatively high upgrade hot water temperatures (141.5 ºC) and low cooling water temperatures (15 °C).

Based on previous designs, the total heat transfer area of the AHT has been selected to meet the requirements in terms of upgraded heat flow under given operating conditions (see Figure 3). In this figure, the absorber capacity of the AHT is plotted against the driving temperature difference ΔΔt, that is defined in equation, with R being a constant around 1.15. (1). The so-called double temperature difference ΔΔt expresses the driving potential of the AHT for heat upgrade. For the nominal capacity of 347 kW, the ΔΔt value should be around 22 K. The figure also shows that for operating conditions like those reported for previous AHT developments, (ΔΔt =30 K) the designed AHT could provide around 500 kW

$$\Delta\Delta t = (t_G - t_A) - R \cdot (t_C - t_E) = R \cdot (t_1 - t_0) - (t_2 - t_1) \qquad (1)$$

As presented in the left diagram of this figure, a ΔΔt value around 22 K can be obtained either by operating evaporator in generator in parallel with 88ºC, or operating them in series, with 90ºC hot water entering the evaporator, and the hot water leaving the evaporator entering the generator. These alternatives have been considered because the operation of an AHT with parallel flow to the evaporator has a larger risk for crystallization,

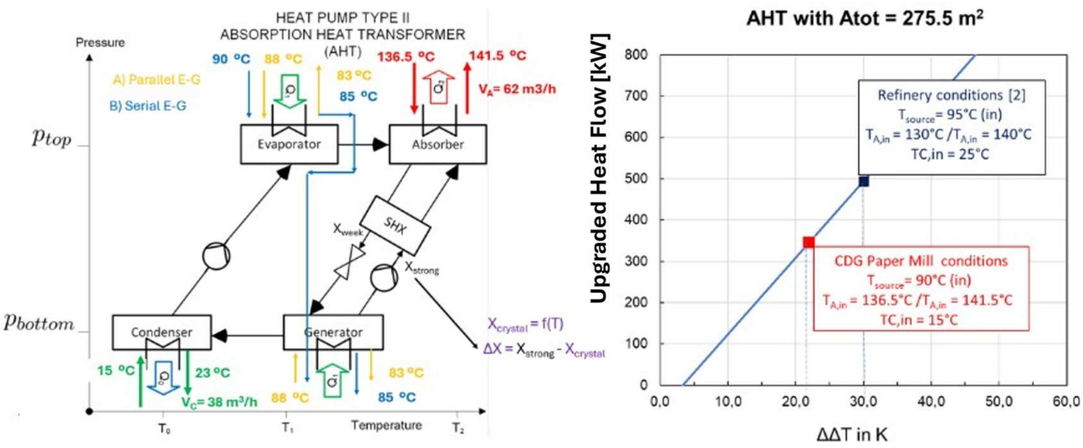

Fig. 3. AHT working conditions and resulting capacity for a total heat transfer area of 275.5 m2

Table 2 presents that the safety margin before crystallization of LiBr inside the AHT ($\Delta X_{,crit}$) using a parallel flow set up to evaporator and generator and the same heat transfer areas distribution as in previous prototypes, would be too small to guarantee safe operation.

Table 2. Comparison of heat transfer areas distribution and resulting safety margin $\Delta X_{,crit}$

Prototype	A_{tot} (m^2)	A_A (m^2)	A_G/A_A (-)	A_E/A_A (-)	A_C/A_A (-)	$\Delta\Delta t_{nom}$ (K)	$Q_{ABS,nom}$	$\Delta X_{,crit}$ (%)
Pilot scale Refinery Prototype [2]	155.9	43.3	1.1	0.8	0.7	30	250	-
Upscaled AHT 1st Iteration (EG parallel flow)	275.5	76.5	1.1	0.8	0.8	22	345	0.64
Upscaled AHT Final Iteration (EG series flow)	275.5	86.3	0.79	0.93	0.48	22	345	2.74

This is one the main safety risks for the operation of a LiBr/H2O absorption heat pump. By changing from parallel to serial configuration this safety margin can be increased from 0.7 to 1.2%. However, a safety margin of at least 2% would be required for safe operation. Changing the heat transfer areas distribution in the heat pump, this safety margin can be further increased. The total heat transfer area for the main heat exchangers (A: Absorber, G: Generator, E: Evaporator, C:Condenser) has been designed to 275.5 m^2. The following table presents how the safety margin can be increased.

By making these changes in the design, the safety margin for operation $\Delta X_{,crit}$ increases from 0.64% to 2.74%, allowing not only for more safe operation but also for operation with changing inlet conditions. This is especially important for operation that combines relatively large driving hot water temperatures and low cooling water temperatures.

4. Combined operation of AHT, Flash Tank and Thermocompressor

As presented in Table 1, the system has been designed for 62 m^3/h of upgraded hot water at the absorber. The system could also be operated with lower flow rates, which reduces the electrical consumption of the pump A (see Fig 2) and increases the electrical COP of the AHT. However, as presented in Table 3, operating with smaller external absorber flow rates but keeping the pressure in the Flash Tank ($t_{A,in}$=t_{FT}=136.5ºC for p_{FT}=3.3 bar(a)). would result in higher delivery temperatures ($t_{A,out}$).
In order to keep the driving temperature $\Delta\Delta t$ = 22 K and keep the nominal heat upgrade capacity at 345 kW, the average cooling water temperature t_C should be reduced, what can be accomplished (by increasing the cooling water flow rate V_c. In this way, the electrical Coefficient of Performance COP_{EL} of the steam producing AHT (COP_{EL} =Q_{abs}/ (W_{ELint} +W_{ELPVa}), with W_{ELint} being the consumption of the pumps inside the AHT and W_{ELPVa} being the consumption of the pump in the upgraded heat circuit) can be optimized depending on AHT capacity for the available conditions.

Table3. change in flow rates for adjusting capacity with ΔP_{Va} and electrical consumptions monitored during commissioning)

for all three cases: $t_{E,in}$=90ºC, $t_{G,out}$=80ºC t_{Cin} = 15ºC t_{Ain} = t_{FT} = 136.5ºC Q_{ABS} = 347 kW	taout = Tft,in (ºC)	$t_{C,out}$ (ºC)	Vcw (m^3/h)	ΔP_{Va} (bar)	W_{ELPVa} (kW)	W_{ELint} (kW)	COP_{EL} (-)
Va = 60 m^3/h	141.7	23.2	38	3.5	10.2	2.33	24
Va = 53 m^3/h	142.4	22.8	40	1.6	4.0	2.33	42
Va = 42 m^3/h	144.0	22.2	43	1.2	2.8	2.33	49

5. First operational results

The commissioning of the heat upgrade system started in October 2025 and was in its final stage by the time this paper has been written. The following figures present the initial results observed while running the system in part load (supplying between 300 and 400 kg/h of steam) for a period around 2 hours during commissioning.

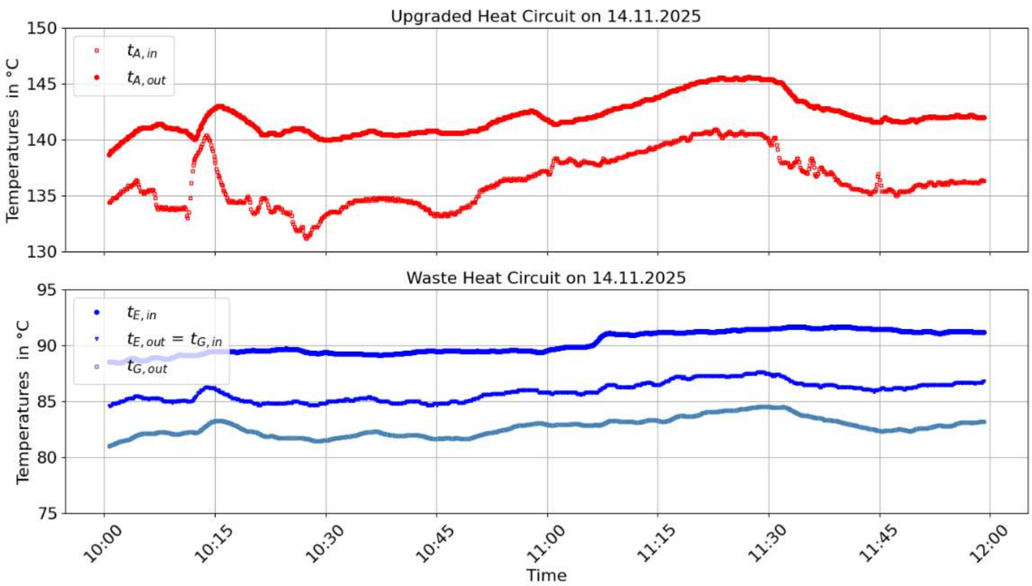

Fig. 5. Waste heat and upgraded heat circuits temperatures measured during 2h of commissioning

The Figure 5 shows how the inlet and outlet temperatures to the absorber and Flash Tank change between 132 and 145ºC (resulting pressures in the Flash Tank between 3.3 and 3.7 bar(a) as it presented in Figure 6), for driving waste heat water t_{Ein} between 88 °C and 91 ºC. Figure 6 presents the flow rate of steam flowing from the Flash Tank to the Thermocompressor and secondly the flow at the outlet of the Thermocompressor. The figure shows how, during a period in which the PID control of the Thermocompressor was tested, it can regulate the outlet pressure at the set point of 6.5 bar(a), using motive steam with 13.3 to 13.4 bar(a) and sucking steam from the Flash Tank at a pressure between 3.5 and 3.8 bar(a).

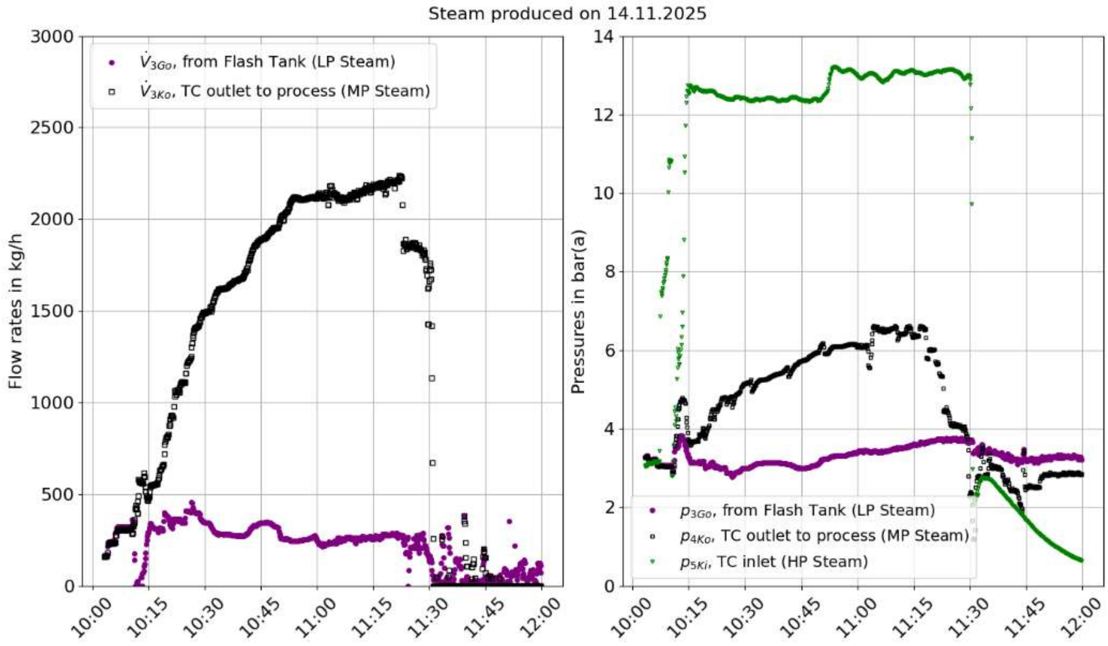

Fig. 6 Steam flow rates and steam pressures measured during 2h of commissioning

6. Conlussions

With an adequate design, a single effect AHT can be combined with a Thermocompressor to provide steam at pressures as high as 6.5 bar(a) using waste heat with 90 ºC, if steam at high pressure is available for the pressure lift. The electrical COP of such a concept, including all necessary pumps, lies between 24 and 50 and can be optimized changing the working pressures and fluid flow rates adapting them to the existing boundary conditions. The first experimental results show that stable operation of the combination of an absorption heat transformer, a Flash Tank and a Thermocompressor for the supply of MP steam with 6.5 bar(a) can be achieved with this concept.

Acknowledgements

This work has been developed under the project “PUSH2HEAT” funded by the Horizon Europe framework of the European Union, Project No. **101069689**. ***https://push2heat.eu/***

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