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Design of Laboratory Scale Absorption Heat Transformer

Marta Santos

CEFT - DEQ - FEUP - Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
eq10066@fe.up.pt

João BLM de Campos

CEFT - DEQ - FEUP - Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
jmc@fe.up.pt

Carlos Pinho

CEFT - DEMEC - FEUP - Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
ctp@fe.up.pt

Abstract. *This work describes the design process of a Single Stage Absorption Heat Transformer with an approximate heating capacity of 5 kW. The design and sizing of the components was based on simulations considering H₂O/LiBr as the working pair and a waste stream temperature of 60 °C. The evaporator, condenser and solution heat exchanger were designed as plate heat exchangers, while the absorber and generator were designed as shell-and-tube heat exchangers. The main specifications of the components are presented, along with their respective 3D sketches. The machine is assembled and the next stage will involve calibration and preliminary tests using the standard H₂O/LiBr mixture. In the future, this setup should enable experiments with different working pairs and additives, as well as different operating conditions.*

Keywords: *absorption, heat upgrade, heat transformer, waste heat recovery*

1. INTRODUCTION

Large amounts of energy from industrial processes are wasted in low temperature thermal flows. In the US, it is estimated that 20 to 50 % of the energy consumed is lost as waste heat in the form of exhaust gases and liquids (Pellegrino *et al.*, 2004). In the UK, close to 72 % of the energy use in industry is attributed to thermal processes, with over a third of that amount being related to low-temperature processes (DECC, 2015; Simeone *et al.*, 2016). In a time when energy prices are constantly fluctuating and environmental concerns are becoming increasingly important, the development or optimization of energy-saving devices is paramount. Absorption heat transformers (AHTs) are thermal machines able to upgrade a portion of the low temperature waste heat to more useful temperature levels for subsequent processes. However, the number of experimental studies reporting such devices is still very limited, which leaves several questions open regarding their performance, especially concerning alternative working pairs other than the most common H₂O/LiBr.

An AHT is particularly useful in applications where waste heat at a relatively low temperature (usually 30-100 °C) is available, and heat at a higher temperature is needed. Some potential applications that have been studied in literature include oil refineries (Donnellan *et al.*, 2014), paper and textile companies (Abrahamsson *et al.*, 1995; Costa *et al.*, 2009; Horuz and Kurt, 2010), water desalination/purification systems (Yari *et al.*, 2017; Gomri, 2010), and hot water solar systems (Ibarra-Bahena *et al.*, 2017), among others. The performance of an AHT, and consequent economic attractiveness, depends on several factors. The mathematical study by Donnellan *et al.* (2014) showed that the unfavorable thermophysical properties of the residue oil waste stream (179 °C) would require an unreasonably large AHT, while the relatively low available quantities of the alternative waste heat stream of naphtha vapor (120 °C) were insufficient to achieve an attractive return on investment. The choice of working fluids and operating conditions (e.g. temperature, pressure) directly impacts the coefficient of performance (COP) and the gross temperature lift (GTL) (Zhao *et al.*, 2005; Wang *et al.*, 2002; Rivera *et al.*, 1999, 2011). The local energy prices (e.g. steam) also have an impact on the economic viability of these systems (Costa *et al.*, 2009).

The vast majority of available literature on AHTs is numerical. Some experimental studies exist, mainly with AHTs operating with the standard working pair H₂O/LiBr (Rivera *et al.*, 2002; Huicochea *et al.*, 2004; Rivera *et al.*, 2015; Cudok *et al.*, 2017; Rivera *et al.*, 2018). Other working fluids that have been studied are water/CarrolTM (Ibarra-Bahena *et al.*, 2015) and water/ionic liquid (Merkel *et al.*, 2018). The aim of this paper is to detail the design and construction process of a laboratory scale Single Stage Absorption Heat Transformer.

2. SINGLE STAGE ABSORPTION HEAT TRANSFORMERS

The heat upgrade in an AHT (Fig. 1) involves a physicochemical process and comprises a generator, a condenser, an evaporator, an absorber and, frequently, a solution heat exchanger (Rivera *et al.*, 1998, 1999, 2011; Yin *et al.*, 2000; Ma *et al.*, 2003; Sözen and Yücesu, 2007; Horuz and Kurt, 2010; Zhang and Hu, 2012). The simplest type of AHT is the Single Stage Absorption Heat Transformer (SSAHT), which operates in a cycle as summarized below.

1. Waste heat is added to the evaporator (\dot{Q}_{EV} , Fig. 1) to vaporize the refrigerant;
2. The vaporized refrigerant is absorbed in the strong solution (higher concentration of absorbent), releasing heat at a higher temperature (\dot{Q}_{AB});
3. The resulting weak solution (lower concentration of absorbent) preheats the strong solution coming from the generator in the Solution Heat Exchanger (SHE);
4. In the generator, heat is added (\dot{Q}_{GE}) to promote desorption of the absorbed refrigerant. The refrigerant follows to the condenser, while the strong solution is returned to the absorber;
5. The refrigerant vapor is condensed in the condenser, releasing heat at a low temperature (\dot{Q}_{CO});
6. The liquid refrigerant returns to the evaporator, restarting the cycle.

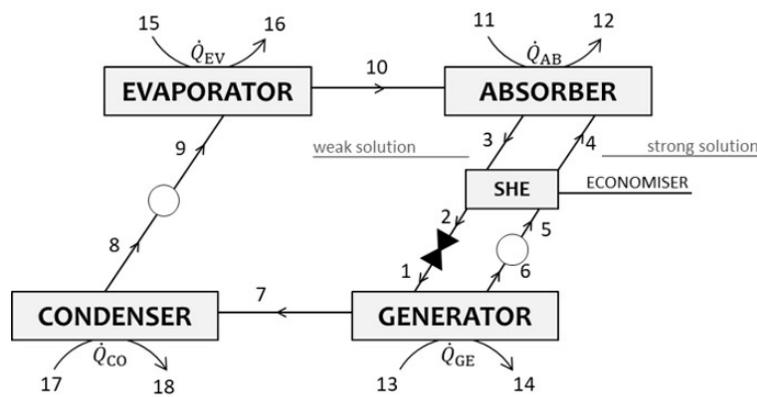


Figure 1. Solution cycle of an AHT

3. NUMERICAL SIMULATIONS

Numerical simulations were carried out in EES (Engineering Equation Software) for a SSAHT machine with a heating capacity of approximately 5 kW. The simulations were performed considering a machine with H₂O/LiBr as the working pair and a waste stream temperature of 60 °C. The numerical model considers the following assumptions:

- The generator and condenser are at a lower pressure, while the evaporator and absorber are at a higher pressure;
- The refrigerant vapor leaving the evaporator is saturated pure water;
- The liquid refrigerant leaving the condenser is saturated;
- The strong solution leaving the generator is at the boiling point;
- The refrigerant vapor leaving the generator is at the equilibrium temperature of the weak solution at the generator pressure;
- The weak solution leaving the absorber is saturated;
- There is no liquid carryover from evaporator;
- The flow restrictor is adiabatic;
- The pumps are isentropic;

- There are no jacket heat losses;
- The logarithmic mean temperature difference (LMTD) expression adequately estimates the latent changes.

The governing equations are the mass and energy balances in each component, which were adapted from Herold *et al.* (2016). The thermophysical properties of water and of the H₂O/LiBr solution in this model came from the EES internal property libraries, specifically those referred to as "water" and "LiBrSSC" within the program. The results of the simulations are shown in Tab. 1, where the relevant variables are presented for each stream. The operating conditions resulting from these simulations were then used to size and design the components of the AHT for the experimental rig.

Table 1. Operating conditions of the SSAHT. The values in bold correspond to the model inputs, and the numbers on the first column correspond to the stream numbers as represented in Fig. 1.

Stream #	h (kJ/kg)	\dot{m} (kg/s)	P (kPa)	Q (-)	T (°C)	x (kg/kg)	v (m ³ /kg)
1	127.8	0.032	3.180	0.008	49.39	0.5027	
2	127.8	0.032	11.506		59.18	0.5027	
3	162.8	0.032	11.506	0.000	75.05	0.5027	
4	163.3	0.030	12.413		73.05	0.5408	
5	125.6	0.030	11.506		55.07	0.5408	
6	125.5	0.030	3.180	0.000	55.06	0.5408	0.0006305
7	2592.7	0.002	3.180		49.39	0.0000	
8	105.1	0.002	3.180	0.000	25.05	0.0000	0.001003
9	105.1	0.002	11.506		25.06	0.0000	
10	2588.8	0.002	11.506	1.000	48.58	0.0000	
11		0.050			60.00		
12					73.24		
13		0.200			60.00		
14					53.37		
15		0.200			60.00		
16					53.24		
17		0.200			10.00		
18					16.77		
19	2588.8	0.000					
20	179.7	0.030			81.12	0.5547	
COP (-)		0.49	FR (-)		14.17		
\dot{Q}_{AB} (kW)		5.54	UA_{AB} (kW/K)		0.5		
\dot{Q}_{GE} (kW)		5.55	UA_{GE} (kW/K)		1.25		
\dot{Q}_{CO} (kW)		5.67	UA_{CO} (kW/K)		0.5		
\dot{Q}_{EV} (kW)		5.66	UA_{EV} (kW/K)		0.75		
\dot{Q}_{SHE} (kW)		1.13	UA_{SHE} (kW/K)		0.39		

4. DESIGN OF THE SSAHT

The main components of the experimental setup are: an absorber, a generator, an evaporator, a condenser, a solution heat exchanger, three pumps, an expansion valve, and four "buffer" tanks. Figure 2 shows a first draft of the main parts of the experimental rig.

4.1 Condenser, Evaporator and SHE

The condenser, evaporator and solution heat exchanger were designed as plate heat exchangers. This maximizes the ratio between equipment size and heat transfer area, and at the same time allows better flexibility in terms of future adjustments (e.g. adding/removing plates to increase/decrease the heat transfer area). All three plate heat exchangers are designed for countercurrent operation and their specifications are summarized in Tab. 2.

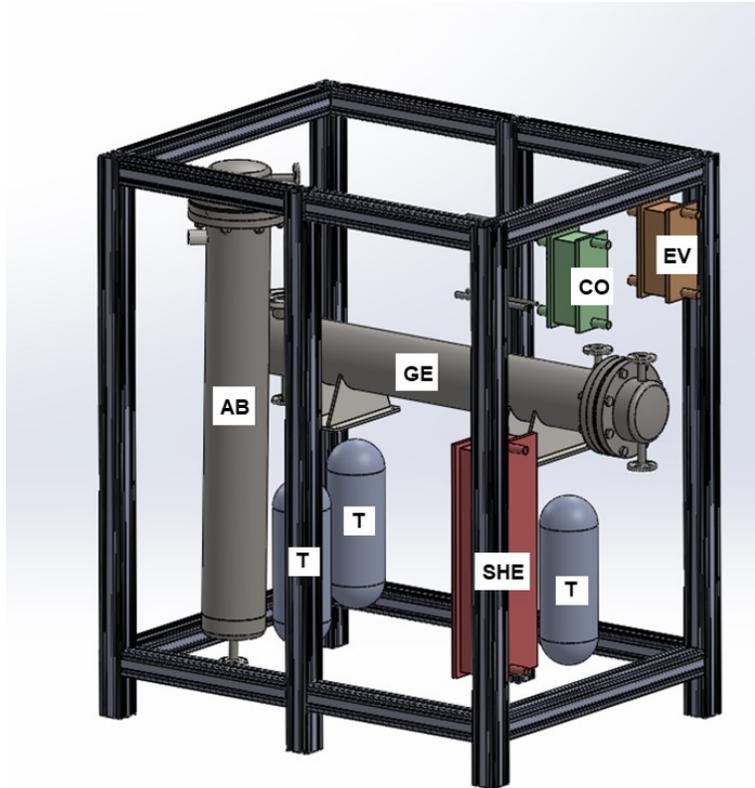


Figure 2. Sketch of the SSAHT experimental setup. AB-absorber, GE-generator, CO-condenser, EV-evaporator, T-tank.

Table 2. Specifications of the plate heat exchangers.

	Side	Fluid	\dot{m} (kg/s)	T (°C)		P (kPa)		Q (kW)	A (m ²)	# plates
				In	Out	In	Out			
CO	Hot	Water vapor	0.002	49.0	25.1	3.18	3.18	5.69	0.09	7
	Cold	Water	0.2	10.0	16.8	200	200			
EV	Hot	Water	0.2	60.0	53.0	200	200	5.86	0.09	7
	Cold	Water	0.002	25.0	48.6	11.5	11.5			
SHE	Hot	H ₂ O/LiBr 50.3 %	0.032	75.1	59.2	11.5	11.5	11.19	3.39	41
	Cold	H ₂ O/LiBr 54.1 %	0.030	55.1	73.1	11.5	11.5			

4.2 Generator

The generator is a U-tube shell-and-tube heat exchanger and was designed for horizontal flooded operation, as shown in Fig. 3. The specifications of this component can be found in Tab. 3.

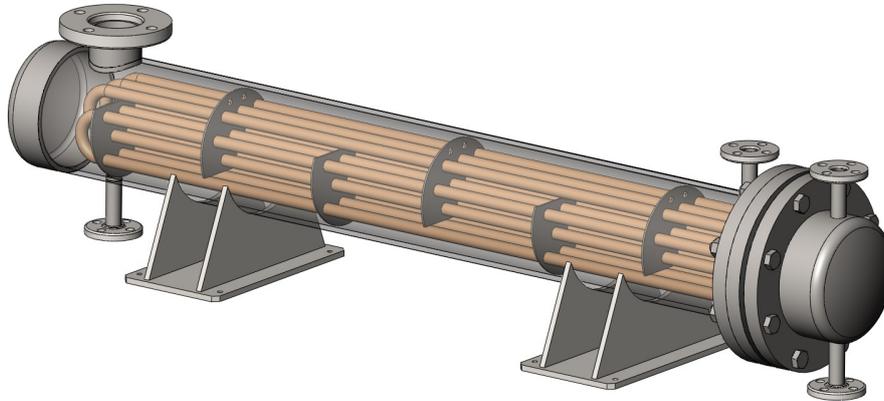


Figure 3. Representation of the generator designed for this study.

Table 3. Specifications of the generator.

Side	Fluid	\dot{m} (kg/s)		T (°C)		x % (kg/kg)		P (kPa)	Q (kW)	A (m ²)
		In	Out	In	Out	In	Out			
Shell	H ₂ O/LiBr	0.032	0.03	49.4	55.1	50.3	54.1	3.18	5.5	0.09
	Water vapor	-	0.002	-	49.4	-	-	3.18		
Tubes	Water	0.2	0.2	60.0	53.4	-	-	200		

4.3 Absorber

The last major component is the absorber, which is similar to the generator: a U-tube shell-and-tube heat exchanger of identical size, as shown in Fig. 4. However, the absorber is placed vertically in order to enable absorption of the refrigerant (water vapor) into the absorbent (H₂O/LiBr mixture) as a falling film along the length of the tubes. A standard heat exchanger was modified to include a solution distribution ring with twelve 1 mm orifices which will spray the absorbent mixture H₂O/LiBr onto the surface of the tubes (Fig. 5). Table 4 details the specifications of the absorber heat exchanger.

Figure 6 shows the experimental setup at the first stage of the construction process.

4.4 Measurement equipment

Continuously measuring data at several points of the process is essential to guarantee the necessary operating conditions, as well as to calculate and compare the final performance criteria. The data to be measured are: temperature, pressure, mass flow rate, concentration, and heat input. Considering this, the necessary measurement instruments and their general specifications were selected and are presented in Tab. 5.

Table 4. Specifications of the absorber.

Side	Fluid	\dot{m} (kg/s)		T (°C)		x % (kg/kg)		P (kPa)	Q (kW)	A (m ²)
		In	Out	In	Out	In	Out			
Shell	Water/LiBr	0.030	0.032	73.1	75.1	50.3	54.1	3.18	5.5	0.09
	Water vapor	0.002	-	48.6	-	-	-	3.18		
Tubes	Water	0.05	0.05	60.0	73.2	-	-	200		

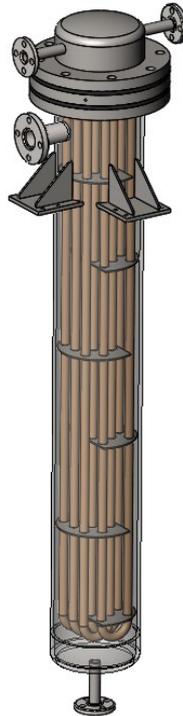


Figure 4. Representation of the absorber.

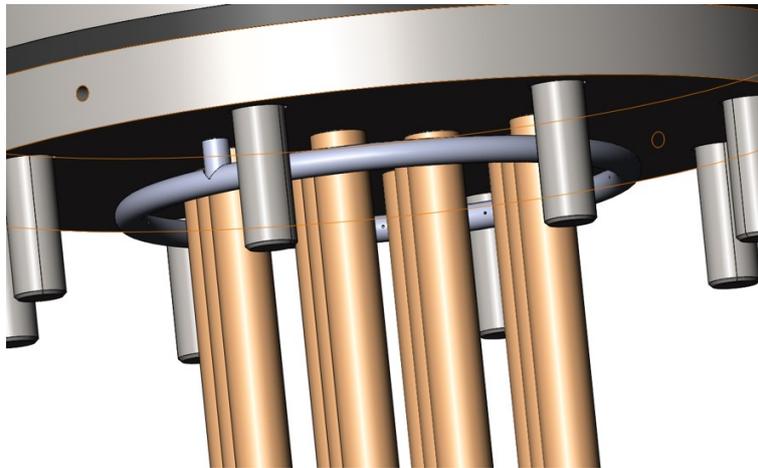


Figure 5. Detail of the absorber solution distribution ring.

Table 5. Specifications of the measurement equipment.

Measurement instruments	Number	Brand/Type	Range	Uncertainty
Temperature indicator	1-14	RS Pro Thermocouple Type T	-75-260 °C	± 1 °C
Pressure indicator recorder	1-6	Jumo Midas Type 401001	0-4 bar	0.5 %
Flow indicator	1-4	Parker Hannifin DFC9000100	1-25 L/min	2 %
Flow & density indicator	5-6	Proline Promass E300 DN08	0-2000 kg/h	0.15 %

5. CONCLUSION

Based on the operating conditions given by the numerical simulations, a Single Stage Absorption Heat Transformer was designed and constructed. The machine was designed for operation with H₂O/LiBr as the working pair, and a waste heat source at 60 °C for an approximate heating capacity of 5 kW. The process of assembly is nearly complete and the calibration and preliminary tests will begin soon. In future studies, other working fluids (such as ionic liquids, ternary



Figure 6. Photographs of the experimental setup.

mixtures and/or certain additives) will be tested and the experimental performance of the AHT compared to that of numerical studies.

6. ACKNOWLEDGEMENTS

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