



Low valued energy sources UPgrading for buildings and industry uses

# LowUP Operation and Validation results for Relevant environment 1 (industrial-upgrading solution)

Deliverable D4.15

**Lead Beneficiary: ACCIONA**  
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## About LowUP

LowUp – Low valued energy sources UPgrading for buildings and industry uses – is developing efficient alternatives to supply heating and cooling for building and industries, based on the use of renewable free energy and heat recovery from non-valuated residual energy sources that are currently wasted. As a result, these technologies will contribute to reducing significantly CO<sub>2</sub> emissions and primary energy consumption, and increase the energy efficiency in buildings.

Led by the Spanish firm ACCIONA, the LowUp project gathers 13 partners (3 large companies, 3 research and technology organisations and 7 SMEs) from 7 European countries. During 48 months, the consortium will develop efficient alternatives to supply heating and cooling for buildings and industries based on renewable free energy as well as non-valuated wasted thermal sources:

- 3 technologies will be developed and demonstrated: one heating and one cooling system for buildings, and one heat recovery system for industrial processes.
- The systems will be demonstrated at 4 demo sites: A Pilot Office building in Seville (Acciona Construcción, Spain), a Waste Water Treatment plant in Madrid (Canal de Isabel II & Acciona Water), a Pulp and Paper mill in Setubal (Portugal, The Navigator Company) and a Student Hall in Badajoz (Spain, University of Extremadura).

*For more information, visit: [www.lowup-h2020.eu](http://www.lowup-h2020.eu)*

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## Executive Summary

This report, D4.15 “LowUP LowUP Operation and Validation results for Relevant environment 2”, has been elaborated within the LowUP Project (GA #723930).

Particularly, this deliverable D4.15 is focused on the HP-LowUP solution, which consists of a waste water heat recovery system combined with a novel design of a heat-pump. For the demonstration and validation of the system, the two developed recovery systems are installed in the waste water treatment plant of Cuenca Baja del Arroyo Culebro (Madrid) and the Navigator Pulp factory (Setubal), while the heat pump system is located at the thermal laboratory of Tecnalia (Guipuzkoa).

The key **objectives** of D4.15 is to collect all information achieved during operation of technologies at relevant environment, in order to validate design requirements through monitoring of results.

As a **result**, this deliverable provides a full description of the activities carried out and explaining performance calculations.

## Keywords

Heat recovery systems, highly efficient heat pump, industrial heat recovery, heat pump, sludge.

## List of acronyms and abbreviations

WWTP	Wastewater Treatment Plant
AD	Anaerobic digestion
CSTR	Continuously Stirred Tank Reactors
COP	Coefficient of Performance
HP	Heat Pump

## 1 Introduction

The objective of this report is to present a summary of the results obtained during: 1) tests carried out on the water-water heat pump manufactured by the company GEA; 2) tests carried out on HReX manufactured by POZZI company within the framework of the LOWUP project.

The results of tests are specified together with problematic during execution; main conclusions about tests carried out and the results obtained, in Laboratory of Thermal Systems and Energy Efficiency of TECNALIA (Azpeitia) for HP, at Setubal Pulp&Paper factory and Madrid Wates water treatment plant for HReX, are here reported.



*Figure 1: Containerized HP solution during testing at Tecnalia Lab*

The main objective of deliverable D4.15 is to present data from activities of characterization and operation of HP LowUP under relevant working conditions, as required by necessity of supplying virtual thermal load of industrial demonstrators, using virtual heat from HReX system.

In this context, the specific objectives for the LowUP characterization and operation are the following:

- stable and continuous operation of the LowUP system in relevant operational environment, for the calibration and validation of technology
- implement different variable thermal loads for testing efficiency and reliability of simultaneous heating and cooling concepts;
- perform parametric studies with the objective to achieve reliable conclusions about the impact that LowUP system could plan in future market..).



## 2 Presentation of the systems

LowUP project is focused on development of a novel, effective and reliable heat pump based system, and 100% thermal powered by residual and rejected low temperature energy sources, for application at industrial processes with temperatures below 90 °C.

This temperature upgrading solution is based on the combination of heat recovery technologies, from low valued energy sources like rejected and process waste heat (20-30°C), with high efficiency-high temperature water-to-water heat pump for the production of process heat between 60-80°C.

HP-LowUP system is composed by following technologies.

- High efficiency electrically driven heat pump.
- Sewage water heat recovery system based on Water-to-water or Sludge/wastewater-to-water heat exchangers.



Figure 2 and Figure 3. Image of heat exchanger, installed in the pilot of Madrid (front view).



Figure 4. Heat recovery system and auxiliary systems after their installation in Setubal.



### 3 Heat Pump Start-up and Characterization

The tests have been carried out under stationary conditions, following the UNEEN standard 14511-3 - Air conditioners, liquid chillers and heat pumps with electrically driven compressor for heating and cooling of environment.

Here below are reported all working points that have been tested.

Setpoints							
ID	Tout condenser	$\Delta T$ Lift	Tin evaporator	Qload	$\Delta T$	Tin condenser	Control mode
	°C	°C	°C	%	°C	°C	-
1	55	30	25	100	10	45	Mass flow
2	55	25	30	100	10	45	Mass flow
3	55	25	30	75	7,5	47,5	Mass flow
4	55	30	25	75	7,5	47,5	Mass flow
5	55	30	25	50	5	50	Mass flow
6	55	25	30	50	5	50	Mass flow
7	55	20	35	100	10	45	Mass flow
8	55	20	35	75	7,5	47,5	Mass flow
9	55	20	35	50	5	50	Mass flow
10	65	30	35	100	10	55	Mass flow
11	65	30	35	75	7,5	57,5	Mass flow
12	65	30	35	50	5	60	Mass flow
13	65	25	40	75	7,5	57,5	Mass flow
14	65	25	40	50	5	60	Mass flow
15	65	25	40	100	10	55	Mass flow
16	65	20	45	100	10	55	Mass flow
17	65	20	45	75	7,5	57,5	Mass flow
18	80	35	45	100	10	70	Manual
19	80	35	45	75	7,5	72,5	Manual
20	75	30	45	100	10	65	Mass flow
21	75	30	45	75	7,5	67,5	Mass flow
22	75	30	45	50	5	70	Mass flow
23	65	20	45	50	5	60	Mass flow
24	80	35	45	50	5	75	Manual
25	70	30	40	100	10	60	Manual
26	50	30	20	100	10	40	Mass flow
27	60	30	30	100	10	50	Mass flow
28	55	25	30	50	5	50	Mass flow
29	55	30	25	50	5	50	Mass flow
30	65	30	35	50	5	60	Mass flow
31	55	15	40	50	5	50	Mass flow
32	55	15	40	75	7,5	47,5	PI
33	55	15	40	100	10	45	PI
34	55	15	40	100	10	45	Mass flow
35	70	30	40	100	10	60	PI
36	70	30	40	100	10	60	Mass flow
37	70	35	35	100	10	60	PI
38	70	35	35	50	5	65	PI

39	65	30	35	100	10	55	PI
40	65	30	35	100	10	55	Mass flow
41	70	25	45	100	10	60	PI
42	70	25	45	50	5	65	PI
43	75	30	45	100	10	65	PI
44	75	30	45	100	10	65	Mass flow
45	75	40	35	100	10	65	PI
46	75	40	35	100	10	65	Mass Flow
47	75	35	40	100	10	65	Mass Flow
48	75	35	40	100	10	65	PI

Table 1 Working point for HP testing

### 3.1 Execution of tests

Certain points initially tested have to be repeated due to lack of stability in the execution of the same, due to imbalances in expansion control valve. Those points are:

- 04/02/2020\_55°C\_25°C\_50%
- 05/02/2020\_55°C\_30°C\_50%
- 10/02/2020\_65°C\_35°C\_50%

In order to obtain adequate stability for all tested points, a specific and tailored update of heat pump control software has been carried out by GEA, specifically focusing on regulation of expansion valve, which gave instability during above failed tests.

A part from control mode initially implemented at factory for normal operation of expansion valve, named “mass flow”, and apart from manual mode for those critic working points close to limits of the machine, a new control mode named “PI” (proportional – integrative) has been implemented.

This new controls implemented during execution of test, allowed achieving better stability during tests and operation; furthermore comparison between different operation modes for control of expansion valve, has also been executed and are showed in this document.

Here below the results achieved during tests of above points, ordered by ID:

ID	Tin condenser °C	Tout condenser °C	Tin evaporator °C	Tout evaporator °C	Flow evaporator m3/h	Flow condenser m3/h	Flow refrigerant kg/s
1	45,18	54,69	24,97	20,28	28,57	16,79	0,15
2	45,04	54,94	29,99	25,11	32,65	18,74	0,18
3	47,49	55,10	29,98	26,21	32,89	18,92	0,14
4	47,77	55,08	24,99	21,43	28,69	16,58	0,11
5	50,17	55,05	24,99	22,63	28,68	16,62	0,08
6	49,92	54,86	30,00	27,52	34,25	19,68	0,09
7	45,06	54,81	35,01	30,22	40,77	22,33	0,21
8	47,68	55,14	35,04	31,38	41,00	22,38	0,16
9	49,95	55,01	35,04	32,56	41,09	22,46	0,11
10	55,02	64,92	35,04	30,14	35,79	20,21	0,20
11	57,51	65,10	35,03	31,23	35,87	20,53	0,15
12	59,94	64,99	35,03	32,49	35,79	20,56	0,10
13	57,53	64,98	40,11	36,42	43,90	24,13	0,18

14	60,03	65,16	40,11	37,56	44,00	24,16	0,13
15	55,02	64,94	40,00	35,06	42,55	23,46	0,23
16	55,05	65,10	45,07	40,01	49,00	26,56	0,27
17	57,53	65,12	45,06	41,14	49,16	27,26	0,21
18	70,00	80,07	45,13	40,09	44,24	25,04	0,26
19	72,51	80,38	45,13	41,17	44,24	25,05	0,21
20	65,04	75,02	44,95	40,02	47,62	26,01	0,26
21	67,63	75,29	44,94	41,09	48,10	26,57	0,21
22	70,12	75,29	44,93	42,29	48,13	26,64	0,14
23	59,96	65,16	45,05	42,41	52,72	28,11	0,15
24	75,10	80,03	45,04	42,56	47,72	26,61	0,14
25	59,97	69,91	40,11	35,23	43,74	23,86	0,23
26	40,06	50,17	20,02	15,09	24,28	13,64	0,13
27	49,94	59,86	30,04	24,98	31,52	18,16	0,17
28	49,94	55,02	30,05	27,47	35,70	20,11	0,10
29	49,91	54,85	25,04	22,60	31,29	17,74	0,08
30	60,02	65,14	35,08	32,55	39,83	21,59	0,11
31	49,96	54,99	40,13	37,57	50,06	26,58	0,14
32	47,45	54,89	40,13	36,36	49,86	26,47	0,20
33	44,93	54,91	40,13	35,12	47,92	25,38	0,25
34	44,91	54,86	40,12	35,12	47,94	25,36	0,25
35	60,07	70,05	40,10	35,06	42,08	23,45	0,23
36	60,08	70,06	40,10	35,05	42,09	23,45	0,23
37	60,10	70,03	35,08	30,08	35,84	20,42	0,20
38	65,07	70,27	35,08	32,41	35,95	20,51	0,11
39	54,95	65,02	35,00	30,02	37,30	20,38	0,20
40	54,91	65,02	34,98	29,99	37,34	20,38	0,20
41	59,99	69,96	45,04	39,99	49,13	26,85	0,27
42	65,04	70,12	45,06	42,41	51,51	28,42	0,15
43	65,04	74,95	45,06	40,07	47,90	26,36	0,26
44	65,03	74,88	45,05	40,09	47,93	26,39	0,27
45	65,00	74,74	34,97	30,09	34,65	19,88	0,19
46	64,97	75,06	34,98	30,07	34,63	19,34	0,19
47	64,99	75,10	39,99	35,01	40,09	22,09	0,22
48	64,97	75,17	39,98	34,97	40,09	22,06	0,22

Table 2 Results of monitoring for HP

Here following the results of tests, used for generation of graphics:

Setpoints	RESULTADOS						
ID	Compressor	Condensing power	Evaporating power	COP heat	EER cool	combined COP	Container consumption
	kWe	kW	kW	-	-	-	kWe
1	32,96	183,13	155,25	5,56	4,71	10,27	33,68
2	32,75	212,81	184,58	6,50	5,64	12,13	33,58
3	25,27	165,00	143,21	6,53	5,67	12,20	25,99
4	25,39	138,86	118,55	5,47	4,67	10,14	25,83
5	17,20	92,98	78,60	5,41	4,57	9,98	17,62

6	17,11	111,41	98,12	6,51	5,73	12,24	18,39
7	32,73	249,92	225,43	7,64	6,89	14,52	33,25
8	24,43	191,33	173,05	7,83	7,08	14,91	24,95
9	16,08	130,26	117,86	8,10	7,33	15,43	16,52
10	41,27	228,71	202,36	5,54	4,90	10,44	41,70
11	31,44	177,94	157,29	5,66	5,00	10,66	32,01
12	20,90	118,69	105,19	5,68	5,03	10,71	21,37
13	30,44	205,20	186,69	6,74	6,13	12,87	31,01
14	21,28	141,56	129,19	6,65	6,07	12,72	21,75
15	41,23	266,09	242,26	6,45	5,88	12,33	41,73
16	40,73	305,20	284,90	7,49	7,00	14,49	41,11
17	30,20	236,06	221,62	7,82	7,34	15,15	30,59
18	56,56	286,30	256,26	5,06	4,53	9,59	56,84
19	42,58	223,81	201,64	5,26	4,74	9,99	43,09
20	51,13	295,43	270,33	5,78	5,29	11,07	52,04
21	39,04	231,23	213,35	5,92	5,46	11,39	39,73
22	25,87	156,50	146,51	6,05	5,66	11,71	26,21
23	19,91	166,93	160,14	8,39	8,04	16,43	20,23
24	28,48	149,01	136,33	5,23	4,79	10,02	28,95
25	46,91	270,73	246,21	5,77	5,25	11,02	47,50
26	30,20	158,58	138,97	5,25	4,60	9,85	32,81
27	37,55	206,30	184,70	5,49	4,92	10,41	38,18
28	17,21	117,08	106,40	6,80	6,18	12,99	17,59
29	17,31	100,44	88,39	5,80	5,10	10,91	17,73
30	21,18	126,05	116,22	5,95	5,49	11,44	21,63
31	15,05	153,37	147,38	10,19	9,79	19,99	16,56
32	24,34	225,86	216,32	9,28	8,89	18,17	25,17
33	33,33	290,62	276,75	8,72	8,30	17,03	33,71
34	32,27	289,74	276,40	8,98	8,56	17,54	32,68
35	47,46	266,82	244,63	5,62	5,15	10,78	47,96
36	47,47	267,12	245,10	5,63	5,16	10,79	48,06
37	46,53	231,28	207,01	4,97	4,45	9,42	47,14
38	23,45	121,40	110,80	5,18	4,72	9,90	23,86
39	42,46	234,37	214,17	5,52	5,04	10,57	42,82
40	41,99	235,41	215,29	5,61	5,13	10,73	42,36
41	47,78	305,25	285,96	6,39	5,99	12,37	48,14
42	23,62	164,48	157,05	6,97	6,65	13,62	23,96
43	52,73	297,38	274,62	5,64	5,21	10,85	53,18
44	51,82	295,71	273,62	5,71	5,28	10,99	52,28
45	49,95	220,50	195,37	4,42	3,91	8,33	50,42
46	49,51	222,04	196,37	4,48	3,97	8,45	50,28
47	50,73	254,22	230,27	5,01	4,54	9,55	51,64
48	51,36	256,12	231,45	4,99	4,51	9,49	52,22

Table 3 Calculation of working points for HP

## 3.2 Graphics

Here below are represented charts with the most significant and representative results of activity done. On one side, COP results have been represented in graphics for “heating” and “cooling” (simple operation) modes first, and for “combined” mode then.

Presented graphics include only those points of operation with at least 3 different positively achieved tests for same setpoint temperature of heat pump (condenser outlet temperature), with purpose of defining efficiency trend along different working points, as previously defined by test plan.

The result is a curve of COP as function of condenser outlet temperature, with evaporator or condenser at full capacity (100%):

- Horizontal axis – outlet temperature from HP condenser (which is the setpoint for this equipment)
- Vertical axis – COP achieved with monitoring during operation

Achieved slopes have different color as function of inlet temperature at evaporator.

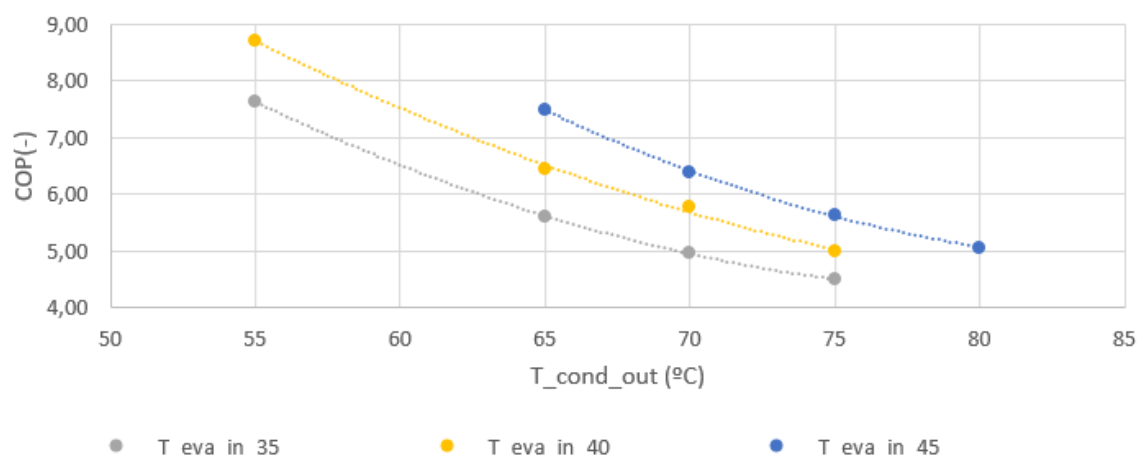


Figure 5: Evaporation slopes with CONDENSER at 100% of capacity

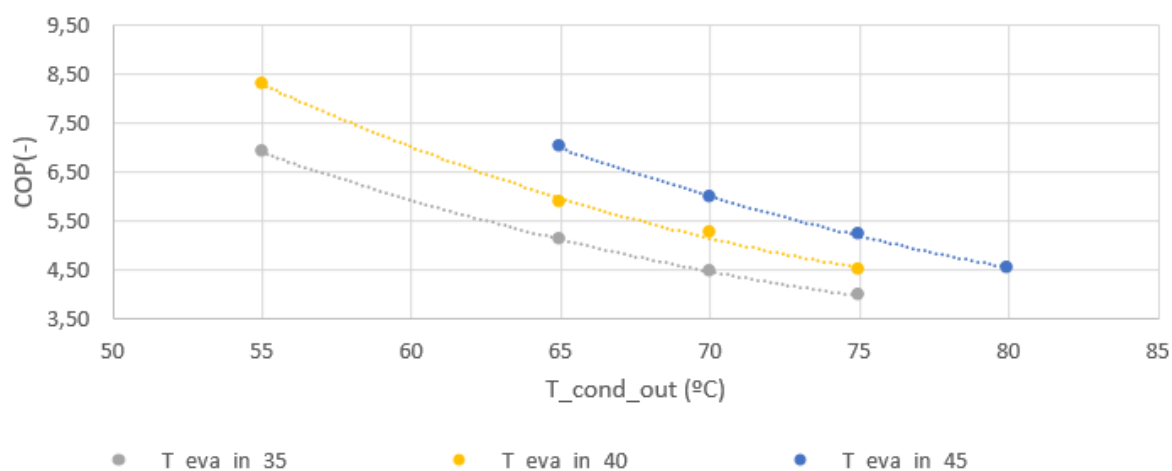


Figure 6: Evaporation slopes with EVAPORATOR at 100% of capacity

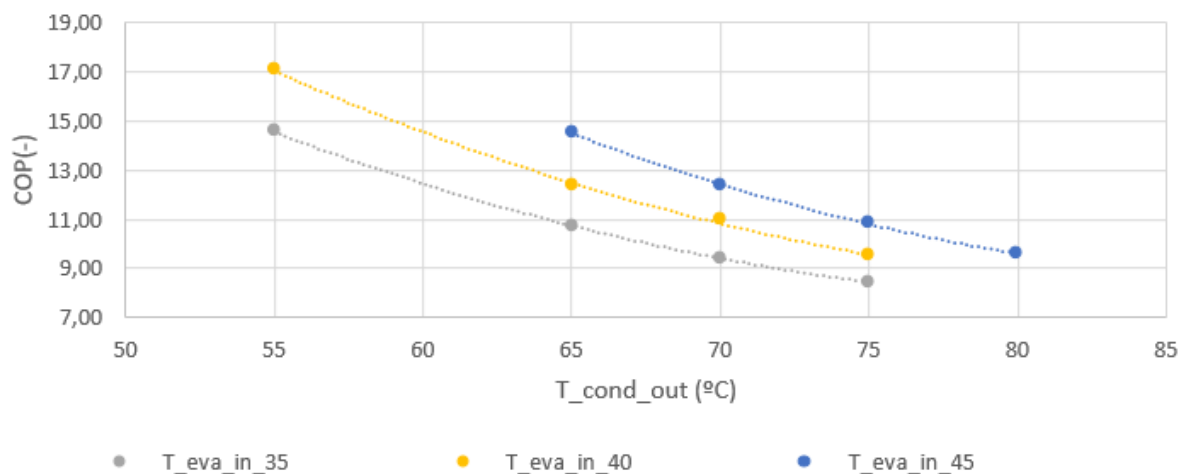


Figure 7: Evaporation slopes with COMBINED 100% of capacity

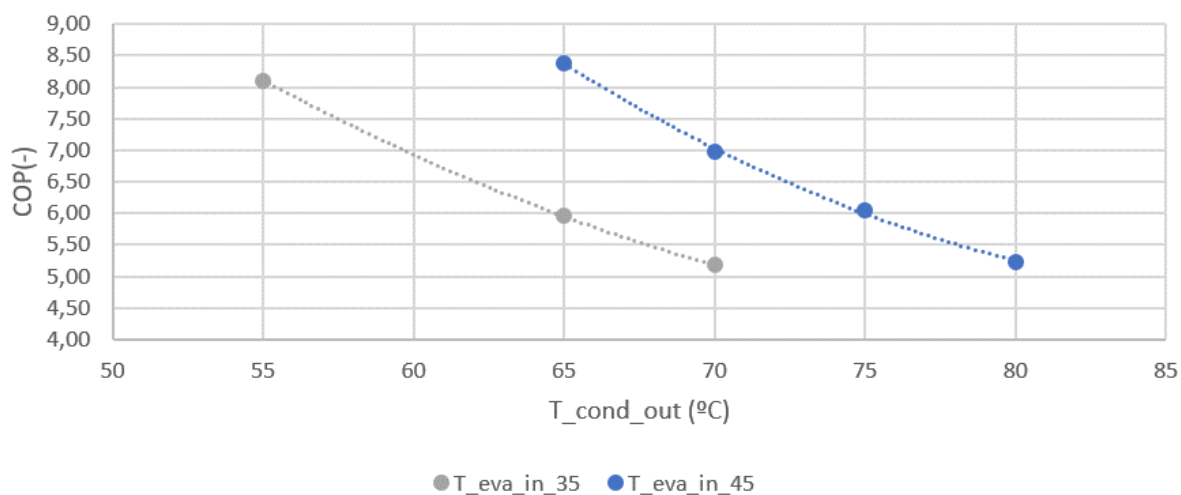


Figure 8: Evaporation slopes with CONDENSER at 50% of capacity

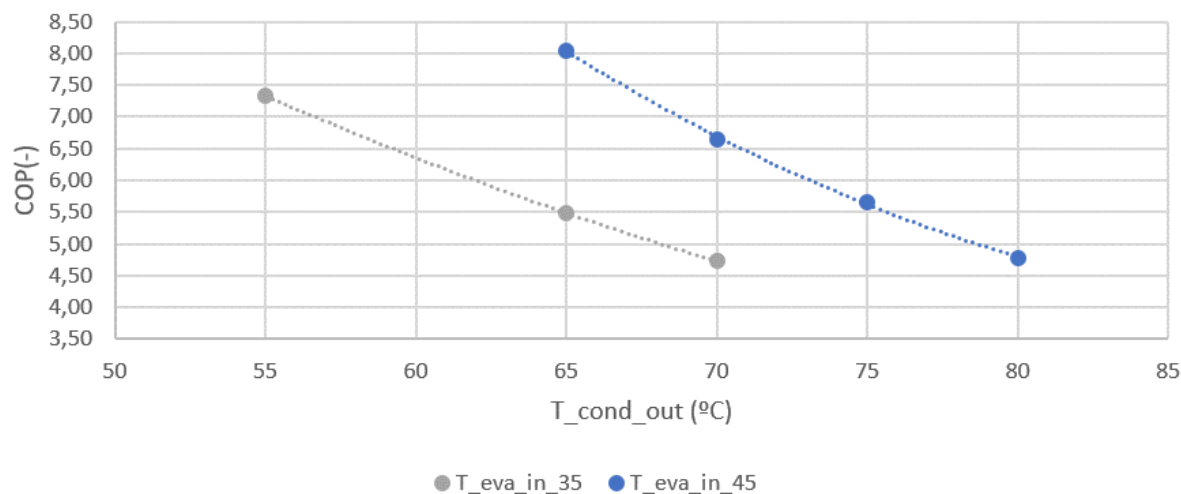


Figure 9: Evaporation slopes with EVAPORATOR at 50% of capacity



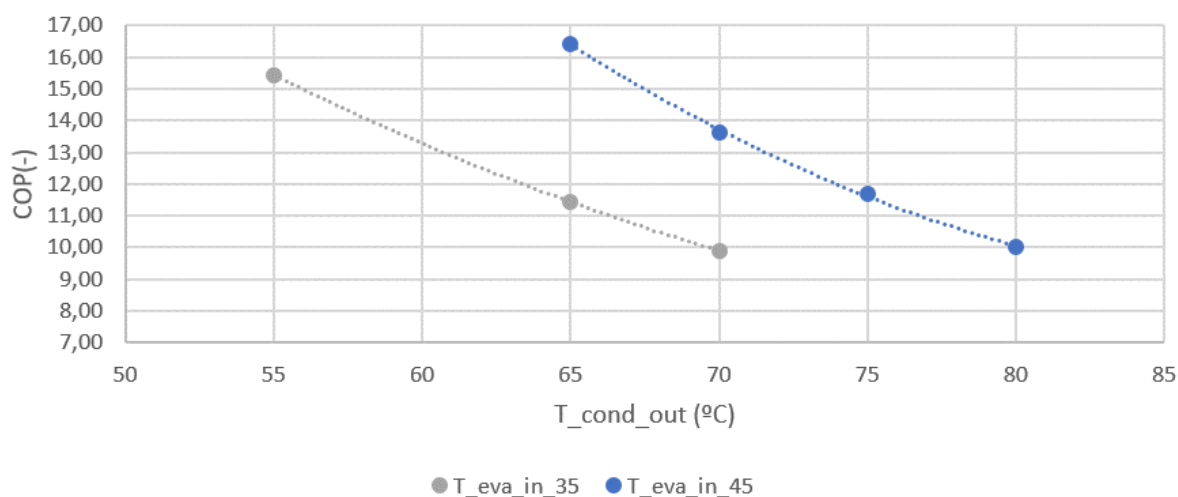


Figure 10: Evaporation slopes with COMBINED 50% of capacity

Operation and monitoring allowed representing graphically achieved difference of performance between theoretical values provided by GEA (according to own simulation/calculation software) and results from tests. In this case only theoretical full capacity values have been used for comparison.

In order to simplify interpretation of graphic, in blue is represented theoretical performance slope, while in orange is represented the same slope of performance but with difference of 10% with respect to blue one. Blue dots represent real position of performance achieved during tests.

- Horizontal axil theoretical power (kW)
- Vertical axis monitored power (kW)

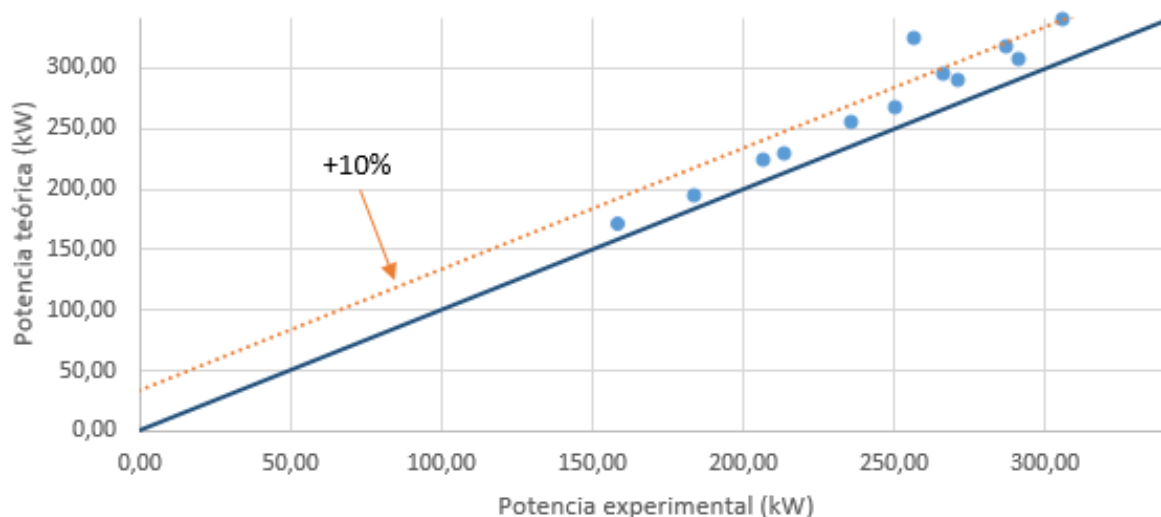


Figure 11: Comparison between theoretical and real delivered power at 100% CONDENSER capacity

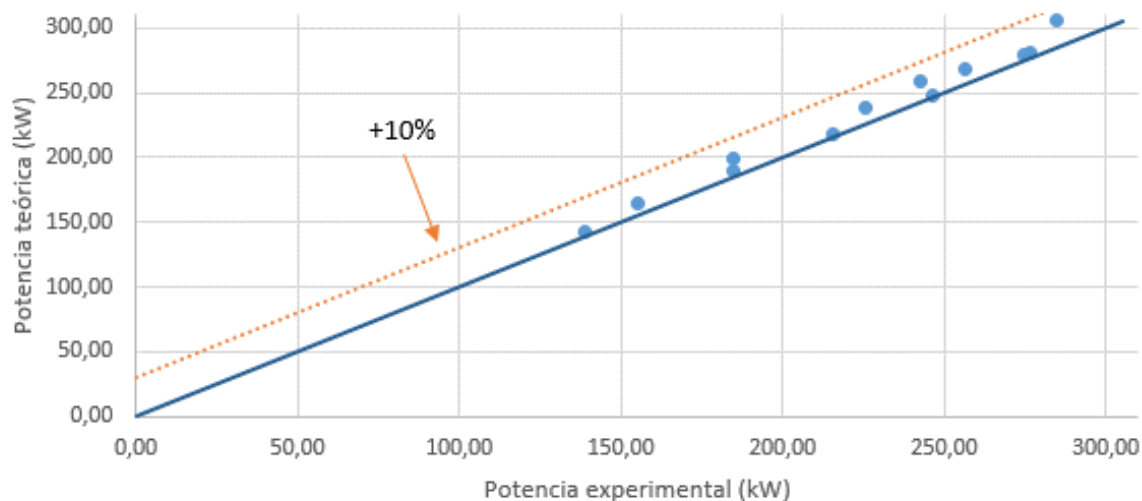


Figure 12: Comparison between theoretical and real delivered power at 100% EVAPORATOR capacity

Next graphic reports difference of real COP with respect to design software:

- Horizontal axil theoretical COP
- Vertical axis monitored COP

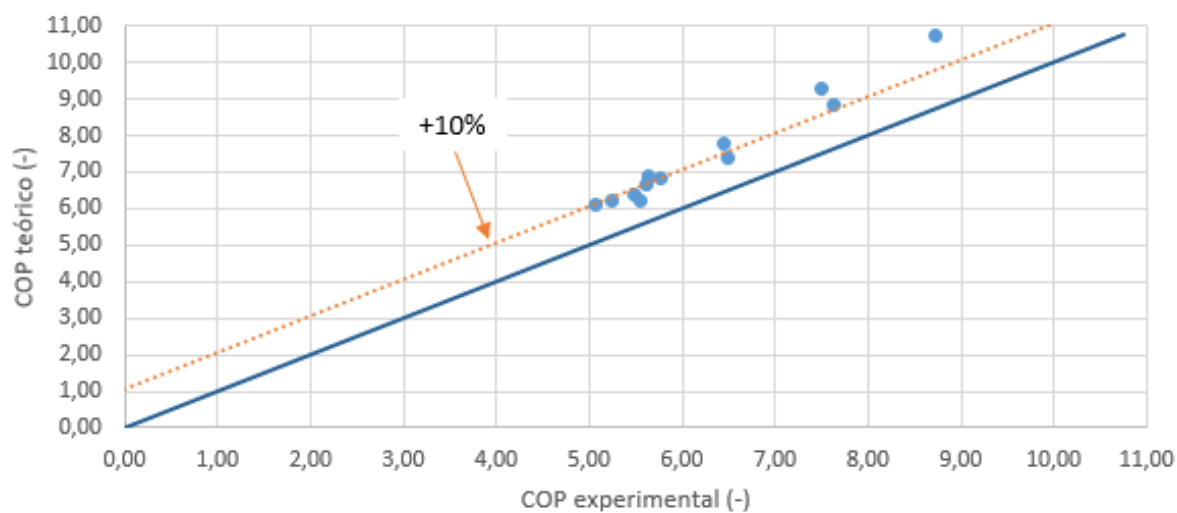


Figure 13: Comparison between theoretical and real delivered COP at 100% CONDENSER capacity

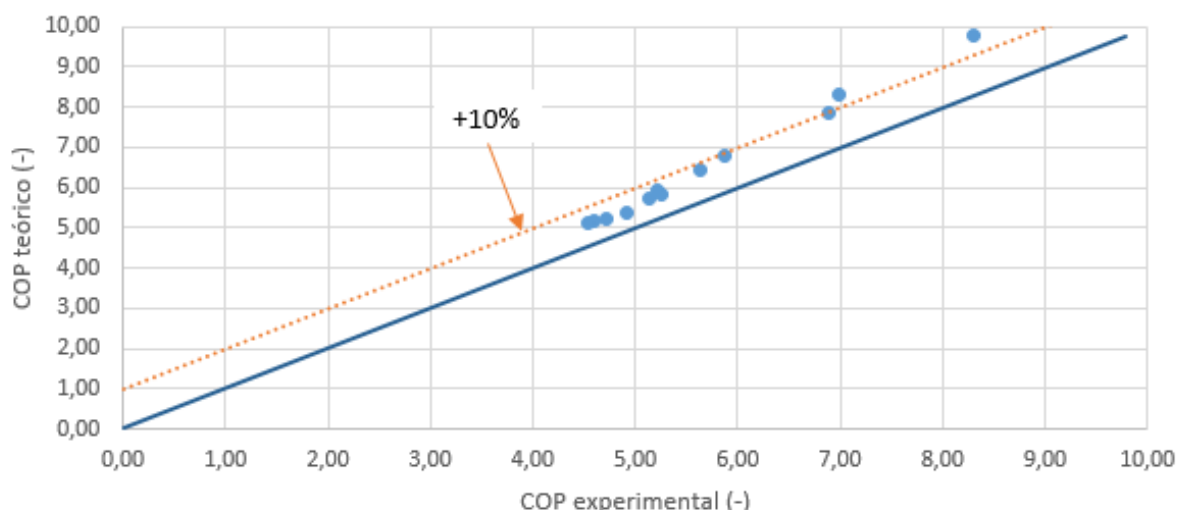


Figure 14: Comparison between theoretical and real delivered COP at 100% EVAPORATOR capacity

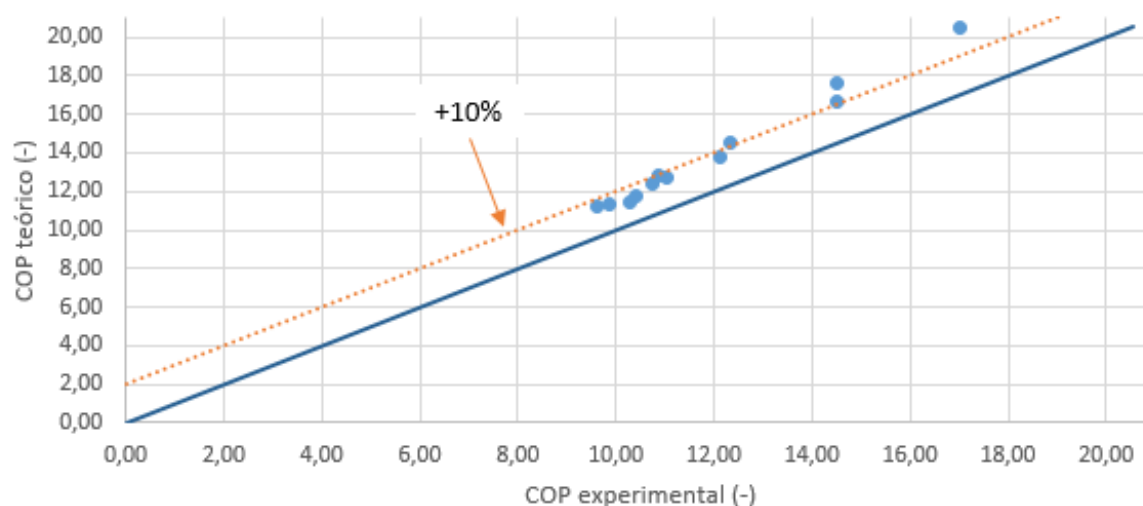


Figure 15: Comparison between theoretical and real delivered COP at 100% COMBINED capacity

### 3.3 Comparison between different operation modes of expansion valve

As explained before, during execution of tests, a control software update of expansion valve occurred for overdriving problems risen during operation for few specific points; consequently, for these points not “corrupted”, it has been possible executing performance tests for PI, Mass-Flow and manual operation modes.

Following is exposed how each expansion valve control mode works:

- PI (proportional-integrative) – It is based on real time sub-cooling at condenser outlet. Measurement of refrigerant ( $\text{NH}_3$ ), at liquid state outcoming from condenser, is compared with condensing temperature, achieved through condenser pressure; difference is sub-cooling. For controlling the valve is set a sub-cooling setpoint (generally 1,5K) which is achieved by the proportional & integral control of degree of expansion(opening) through a feedback loop fed by sensor installed downstream.

- Mass-flow – the controller calculate an estimation of  $\text{NH}_3$  mass volume recirculating through refrigerant loop, as function of compressor characteristics, speed of motor, aspiration pressure and discharge pressure. With this estimation, taking into account technical characteristics of expansion valve, controller calculates the opening that valve should have in each moment according to its boundary conditions. In order to correct possible deviations, due to fact that is a theoretical calculation, sub-cooling energy measured at outlet of condenser is also considered into balance; at same time maximum and minimum limits are set. When limits are overcome, degree of valve opening calculation is corrected until sub-cooling returns within these limits, which generally are 1K and 3K.
- Manual – valve opening value is set manually.

Here below are represented are tested points with requested working conditions:

Setpoints							Control mode
ID	Tout condenser	$\Delta T$ Lift	Tin evaporator	Qload	$\Delta T$	Tin condenser	
	°C	°C	°C	%	°C	°C	-
25	70	30	40	100	10	60	Manual
35	70	30	40	100	10	60	PI
36	70	30	40	100	10	60	Mass flow

Table 4 Working point for different control modes

Here below are represented are tested points with achieved working conditions:

Tin condenser	Tout condenser	Tin evaporator	Tout evaporator	Flow evaporator	Flow condenser	Flow refrigerant
°C	°C	°C	°C	m <sup>3</sup> /h	m <sup>3</sup> /h	kg/s
59,97	69,91	40,11	35,23	43,74	23,86	0,23
60,07	70,05	40,10	35,06	42,08	23,45	0,23
60,08	70,06	40,10	35,05	42,09	23,45	0,23

Table 5 Monitoring for different control modes

Flowing charts show difference in expansion valve regulation control for Mass-flow and PI.

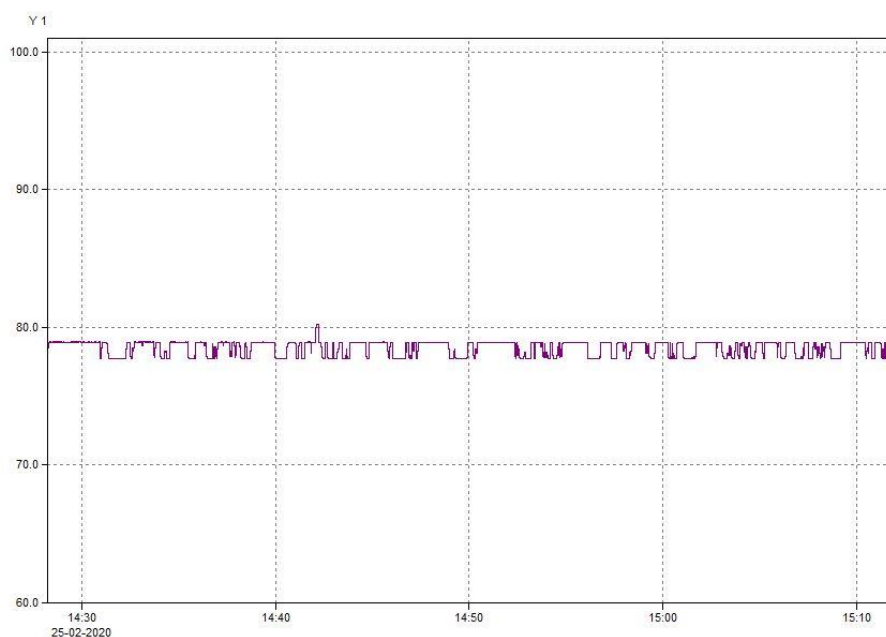


Figure 16: Valve opening with PI control

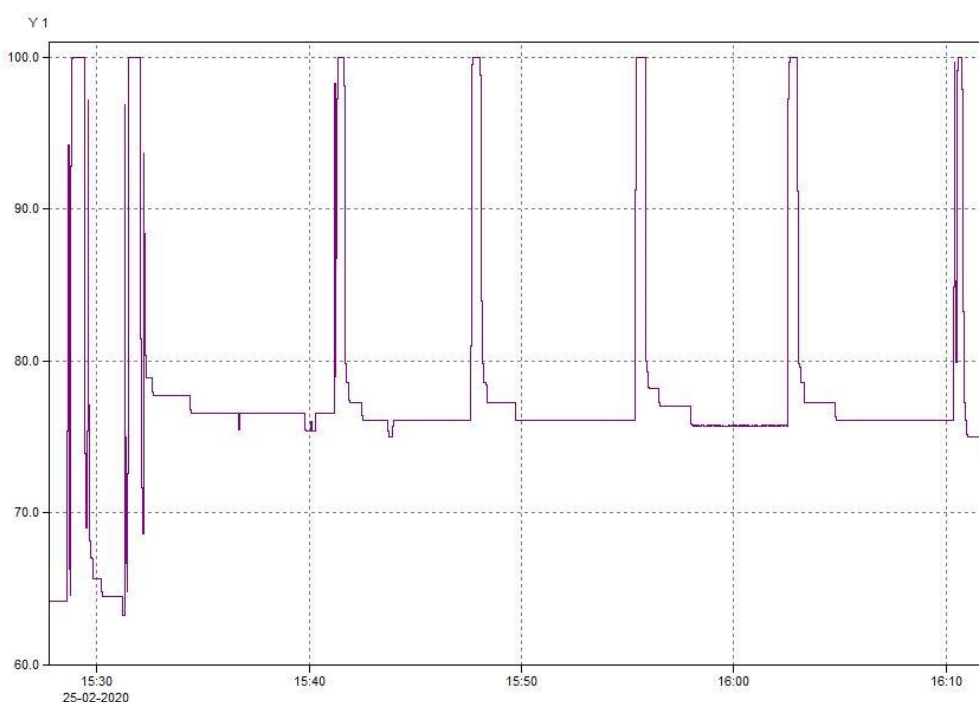


Figure 17: Valve opening with Mass-flow control

Here below are represented are tested points with respective results of operation:

Compressor	T condensation	T evaporator	Condensing power	Evaporating power	COP heat	EER cool	combined COP
kWe	°C	°C	kW	kW	-	-	-
46,91	71,36	32,74	270,73	246,21	5,77	5,25	11,02
47,46	71,79	32,63	266,82	244,63	5,62	5,15	10,78
47,47	71,90	32,62	267,12	245,10	5,63	5,16	10,79

Table 6 Results of different working mode

Among three cases, best result in generated power has been achieved by manual mode (which is not feasible during long term operation); nevertheless all three main parameters (evaporation, condensation and electric consumption) are quite close, with respect to total power.

It has been observed that, for most of tests comparing mass-flow with PI control, electric consumption is slightly reduced for Mass-flow (around 1kW).

## 4 Problems encountered during operation of Heat Pump

During tests, most of faced problems were related with control of unit and with expansion valve, limits of operation of unit and stability of operation points.

### 4.1 Expansion valve

Graphic below shows instability generated by expansion control valve to temperatures outcoming from evaporator and condenser:

- At 50% of capacity – operation conditions were condenser 55°C and evaporator 25°C

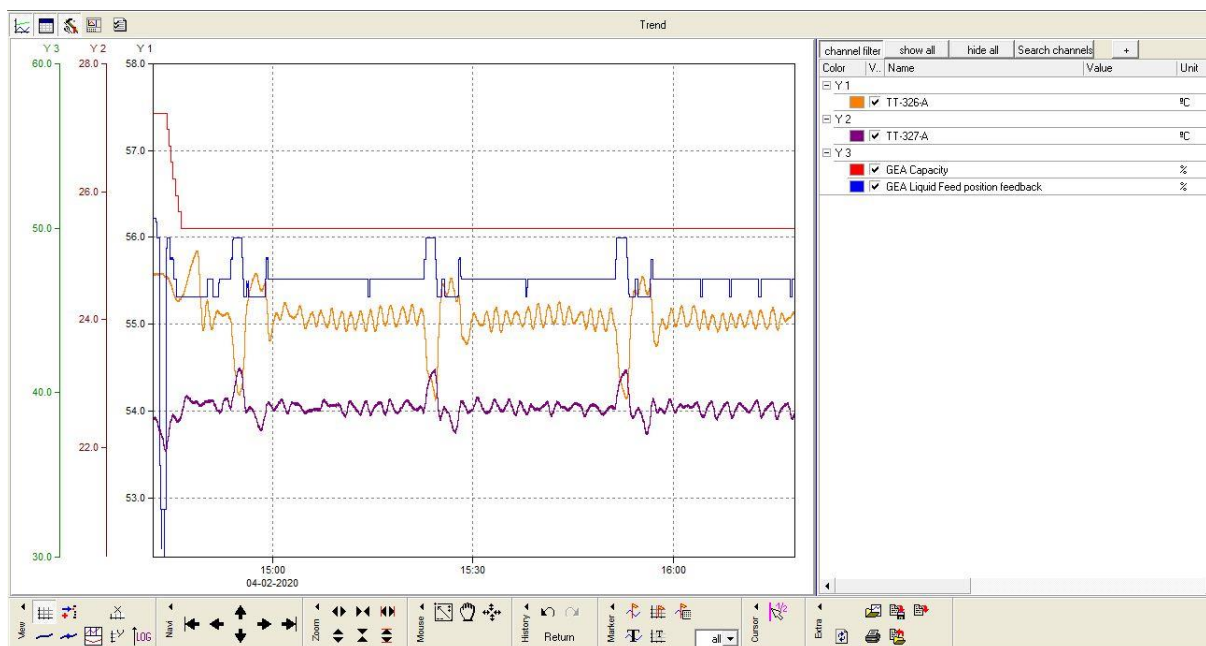


Figure 18: Operation 55°C\_25°C\_50%

In above figure, orange line represents inlet temperature from condenser, while violet is evaporator outlet temperature; blue line is opening of expansion valve, while red is compressor capacity.

It can be detected how, maintaining stable inlets at desired conditions without any other disturbing element, around each 30 min the valve has an unexplained peak of opening of 2,5%; after each peak the original position is recovered within 1 minute.



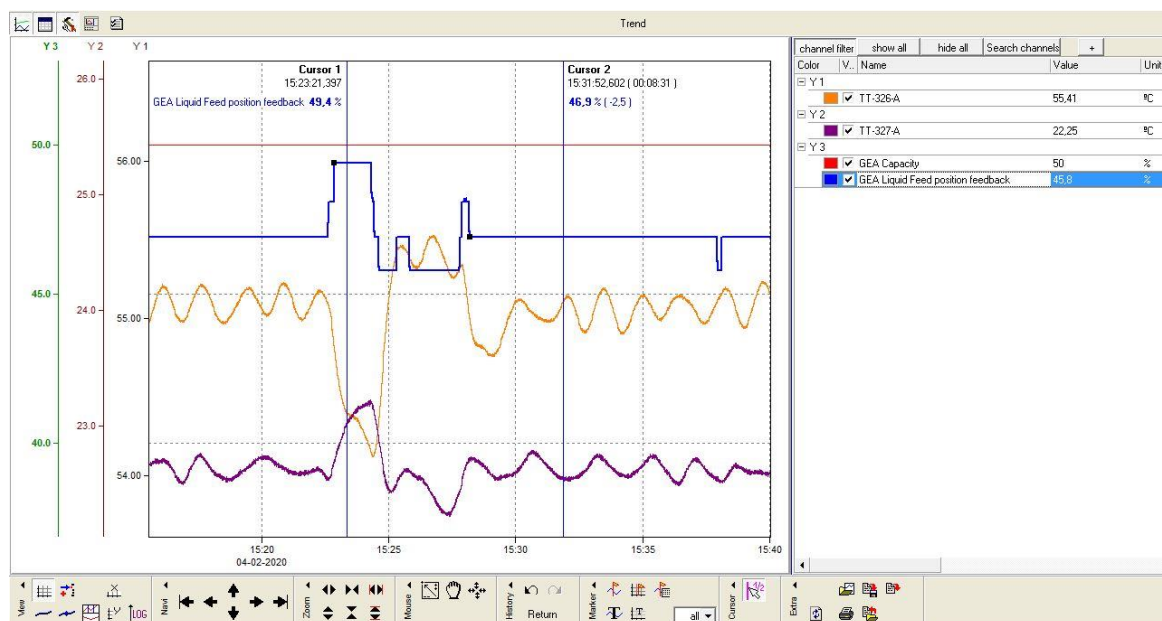


Figure 19: Opening peak for expansion valve

Due to this peak, stability is lost for outlet temperature of both evaporator and condenser. For condenser, variation is 1K of reduction, while for evaporator variation is 0,55K of increment; then original temperature is achieved again.

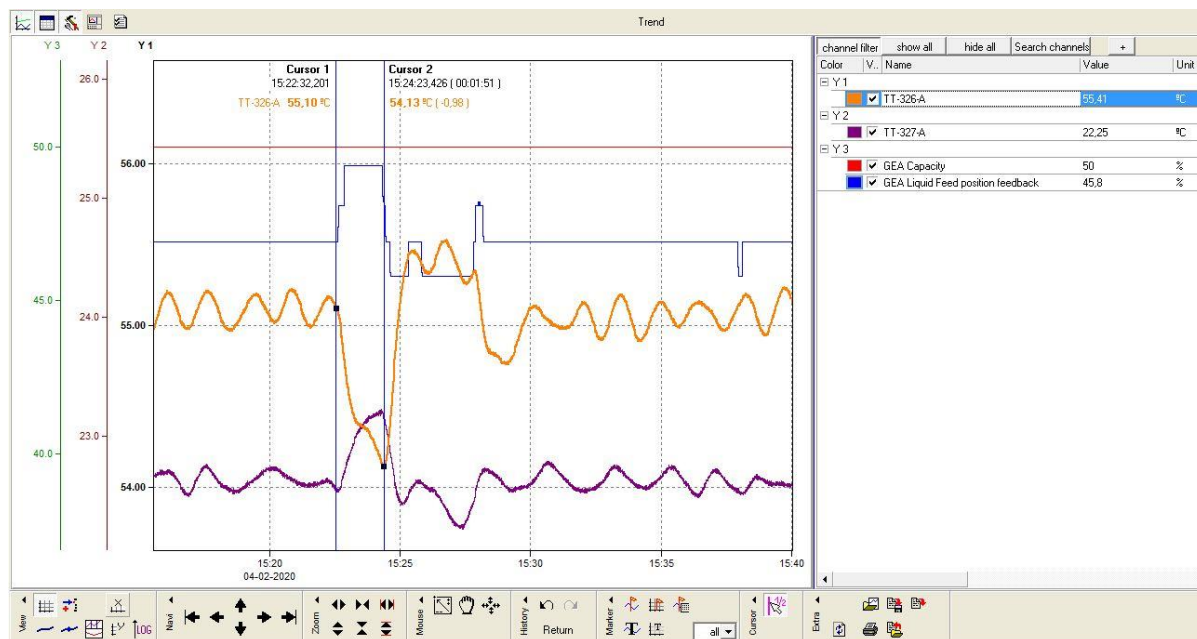


Figure 20: Effect of opening over CONDENSER

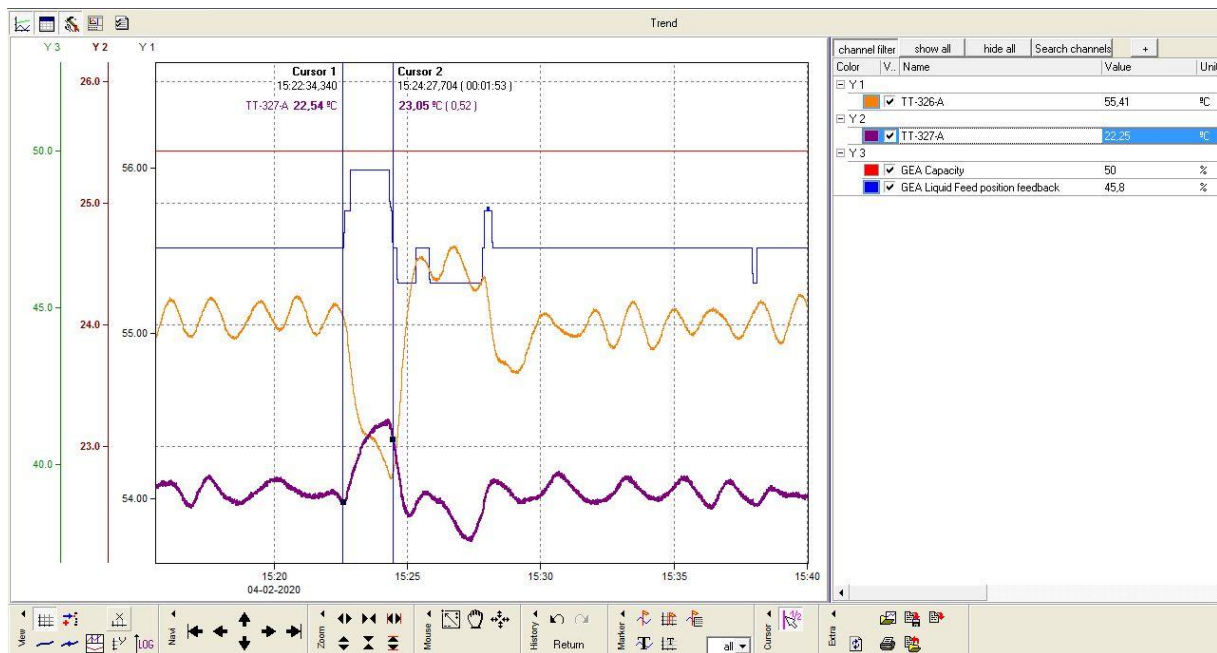


Figure 21: Effect of opening over EVAPORATOR

- At 75% of capacity – operation conditions were condenser 55°C and evaporator 25°C

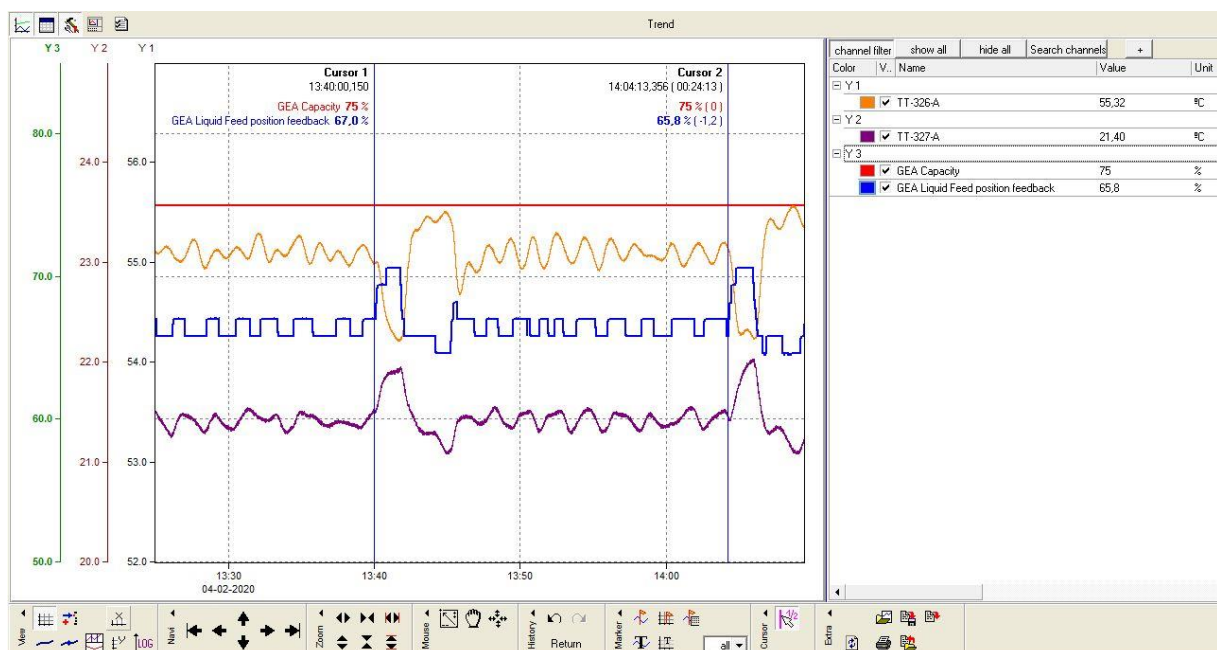


Figure 22: Operation 55°C\_25°C\_75%

In this case expansion valve was regulating between 65-67%, when every 24 min approx valve was opening 3.6%, causing reduction of outlet temperatures.

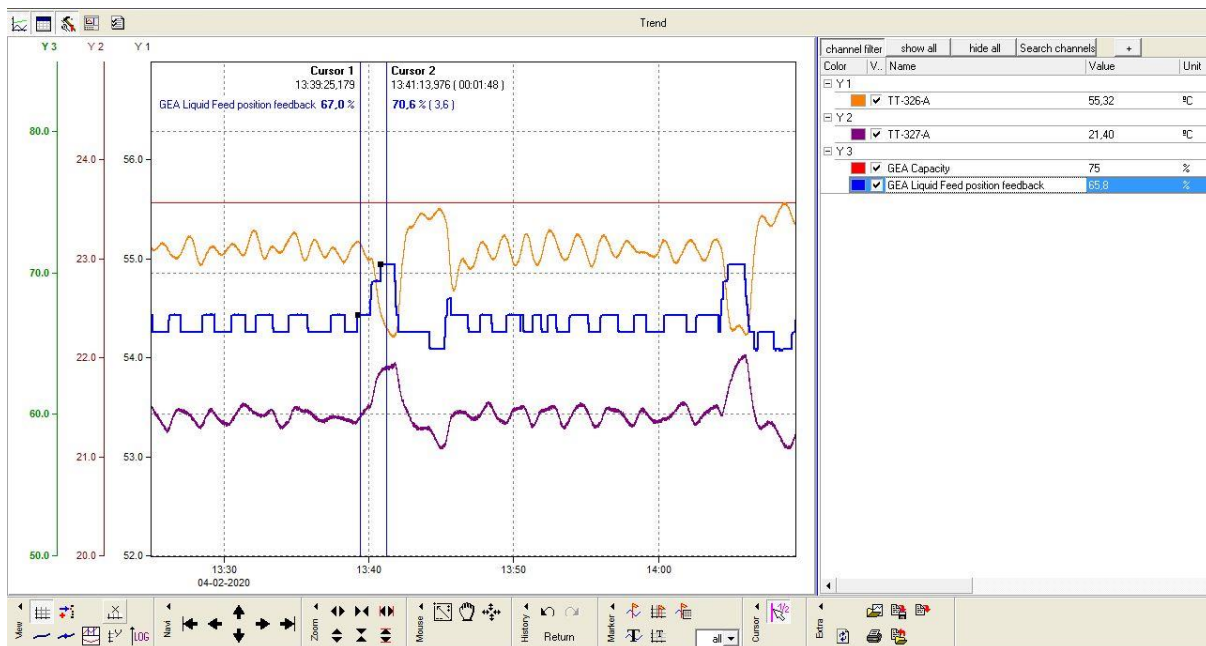


Figure 23: Peak of valve opening and temperature variation

It can be seen how condenser outlet temperature loses stability for approx  $\pm 0,64K$ . Here below is explained how problem was finally solved.

It was detected that oil recovery system was generating fluctuations; it was discovered that solenoid valve Y319.01 (blue circle) was installed the other way round; this was generating instability to evaporator during return cycle of oil to compressor.

Increase of pressure during recovery overcame valve closure resistance, allowing entrance of gas to evaporator through this line, increasing pressure inside it. To avoid this, valve Y319.01 was manually closed.

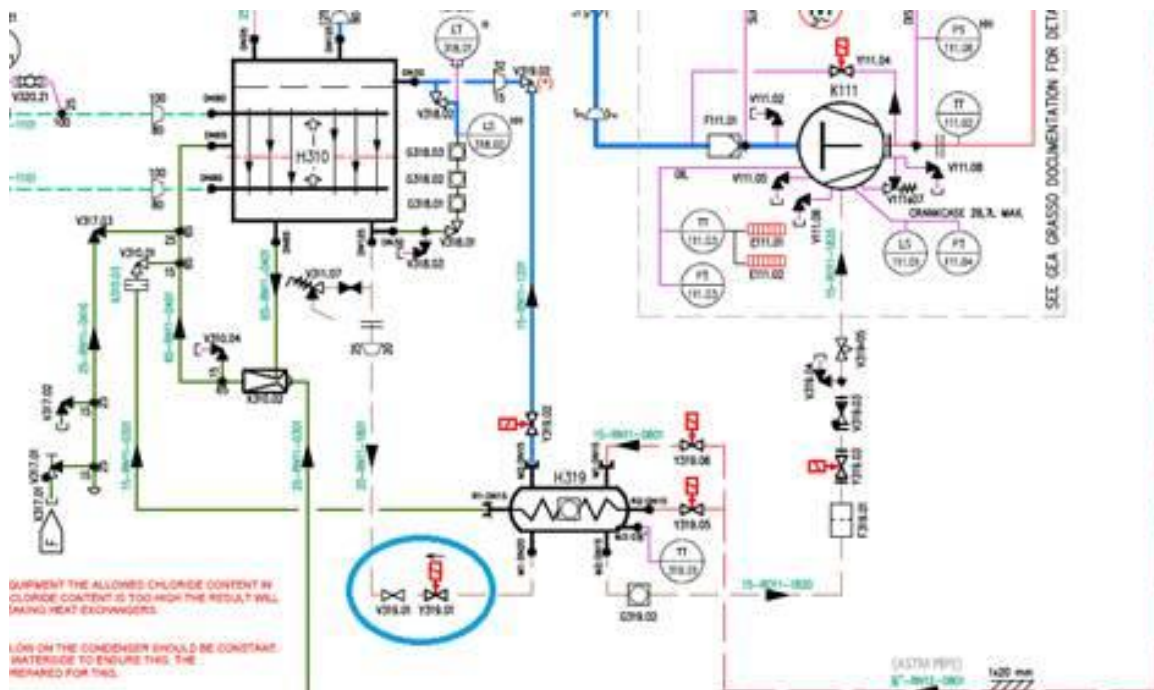


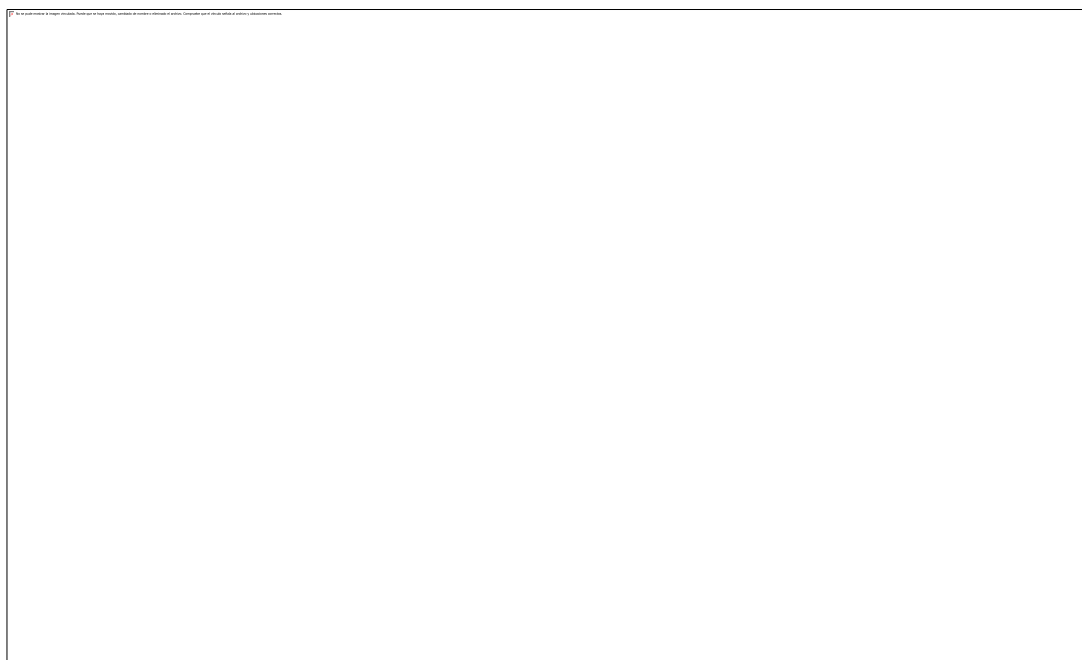
Figure 24: HP refrigerant loop P&ID

## 4.2 Oil recovery system

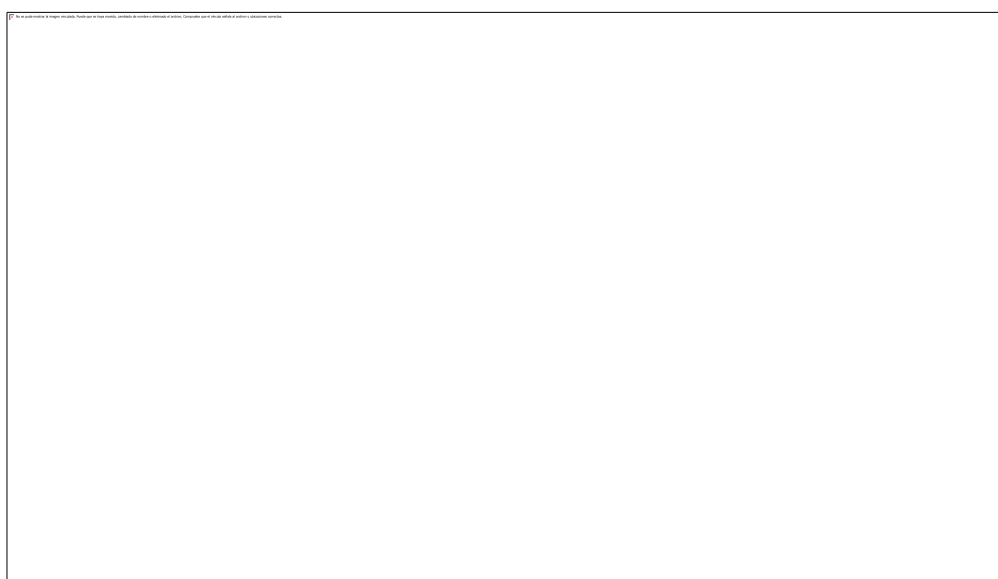
Meanwhile it was detected that, during evaporation cycle of  $\text{NH}_3$  inside recovery tank, thermal energy generation lowered of about 10 kW, during test conditions at 100% of HP capacity.

It wasn't clear if X310.03 device (red circle) had really been installed, because gas entrance to evaporator was direct during  $\text{NH}_3$  evaporation cycle, affecting negatively on efficiency of evaporator.

Solution was achieved bypassing totally oil recovery process, deactivating actions of solenoid valve and removing its installation piping, excepting for 15-RN11-1201, which has been kept open to maintain same level pressure inside evaporation tank and evaporator, as shown in figure below.



*Figure 25: Oil recovery system*



*Figure 26: Oil recovery system controller at OMNI software*

### 4.3 Discharging pressure and suction pressure

Here are reported some problems related with pressure of discharge and suction during tests at following boundaries conditions:

- Outlet temperature for condenser 55°C
- Inlet temperature for evaporator 40°C
- Compressor capacity 100%, 75% and 50%

As soon as evaporation temperature was raising 40°C, liquid low level of refrigerant inside evaporator triggered; as consequence expansion valve lost stability closing between 100 to 5%. During this valve closing-phase, discharge pressure of compressor rose to 45 bars, generating high-pressure alarm and switching off safely the HP unit.

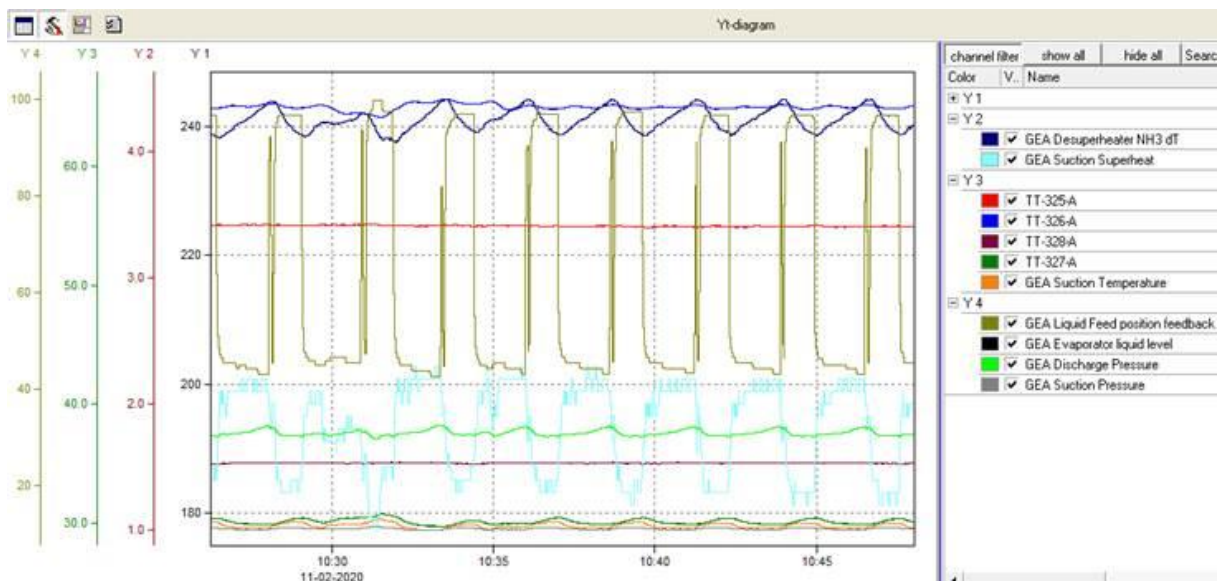


Figure 27: Unstable operation with temperature inlet temperature close to 40°C

With these conditions, no tests with 55°C outlet from condenser and 40°C incoming at evaporator were achievable because of instability of expansion valve. Solution to problem was achieved changing control mode (introduction of PI), so tests at 50, 75 and 100% were fulfilled.

Another case rove with test at following conditions:

- Outlet temperature for condenser 65°C
- Inlet temperature for evaporator 45°C
- Compressor capacity 100%

When temperature rose from 40 to 45°C, suction pressure started increasing (max pressure limit was fixed at 14 bars), when 43,9°C were achieved at inlet of evaporator, suction pressure overcome 14 bars (14,1) and again unit safely switched off.

Solution for tests at 45°C was achieved moving the maximum pressure limit from 14 to 17 bars, which is the top for compressor at suction pressure.



## 5 Heat Pump Start-up and Characterization

This section presents experimental results that were obtained by the operation of the heat exchanger under real operating conditions at P&P factory of Navigator Company in Setubal, Portugal and at WWTP operated by ACCIONA in Madrid. The presented information, achieved by both demos, was used to validate and adjust the mathematical model of the heat exchanger of D3.5 “Dynamic models and HIL emulation”.

The installed system is composed by four main devices. The heat exchanger unit (subject of validation), a dry cooler equipment to emulate different energy demand conditions, as well as a water pump and a sludge pump for the circulation of the effluents of the primary and secondary circuits of the HX. The following figure depicts the installed equipment, which was mounted in a single skid for its easier integration and management.

In case of P&P factory a specific pump has been used, because of contingency of the plant; nevertheless at WWTP it was decided to use directly pressure produced by height of anaerobic digester and regulate the flow through a manual valve, already present in the plant, at entrance un heat recovery unit.

Here below are reported all working points that have been tested.

Water pump flow (l/min)	Sludge pump flow (l/min)	Water inlet temperature (°C)	Water outlet temperature (°C)
80	55	20	25
80	55	22,5	25
80	55	22,5	27,5
80	55	25	27,5
80	55	27,5	30
80	55	30	32,5
80	55	32,5	35
80	55	35	37,5
80	55	37,5	40
80	55	37,5	42,5
80	55	40	42,5

Table 7 Working points

Originally it was planned to operate the heat exchanger with additional sludge/effluent flow at 80 lt/min, but only few points of this case study have been addressed, because of technical problems faced during operation at both demos which reduced number of operating hours of booth units. Problems have been detailed in section 6 of present document.

### 5.1 Execution of tests

All point presented in this section have been tested many times thanks to automatic not supervised execution of operation implemented by CARTIF; depending of air temperature, the control system could activate dissipation in order to achieve a specific clean water temperature, in function of drycooler capacity.



Here below is represented a typical set of test that took place during 8 consecutive days, with constant sludge and clean water flows, with different temperature setpoints for drycooler, as it can be seen through different “staircases”.

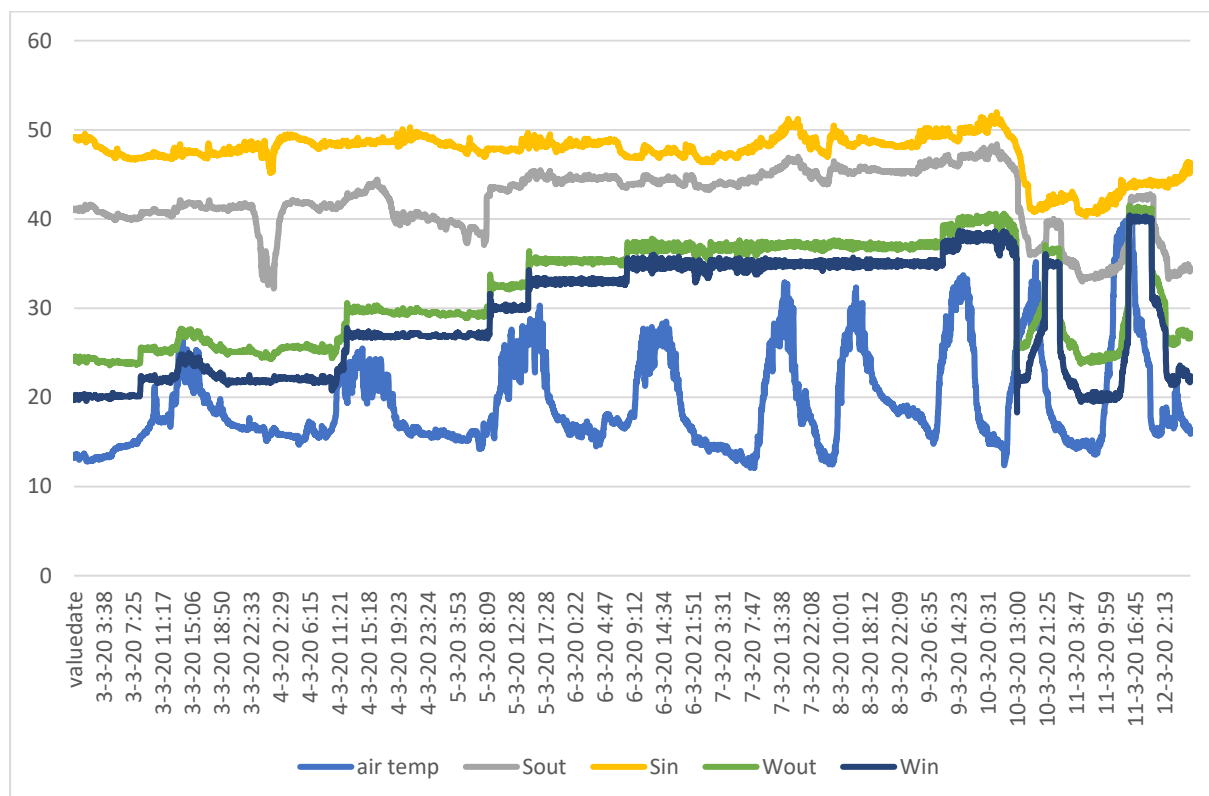


Figure 28. Temperature variation of water according to programmed tests

Sludge, water and air temperature are here represented with inlet and outlet for each fluid, with HReX operating at nominal rotor speed.

Here below are represented the points of operation, and respective calculations, once have been depurated and normalized from operation data. For analysis, only period with at least 15 min of stable conditions (flow and temperatures) have been taken into account.

Tsetpoint °C	Efficiency	Sflow (m <sup>3</sup> /h)	Sout °C	Sin °C	Pow Sludge kW	Wflow (m <sup>3</sup> /h)	Wout °C	Win °C	Pow water (kW)
25°	0,793	2,569	41,801	48,939	21,376	4,276	25,615	22,047	16,950
27,5°	0,793	2,328	41,655	48,766	18,546	4,332	27,780	24,708	14,773
30°	0,797	2,712	41,705	47,487	18,290	4,331	27,161	24,148	14,498
32,5°	0,851	2,928	43,621	47,916	14,644	4,396	32,479	29,997	12,124
35°	0,828	3,037	44,694	48,416	13,180	4,445	35,293	33,022	11,212
37,5°	0,887	2,885	44,256	47,421	10,652	4,478	36,796	34,898	9,443
40°	0,939	3,005	47,125	50,082	10,368	4,619	39,854	37,958	9,734
42,5°	0,963	3,162	42,437	43,950	5,563	4,798	41,039	40,034	5,356

Table 8 Tested point for HReX

## 5.2 Graphics

Here below are represented charts with the most significant results of activity done.

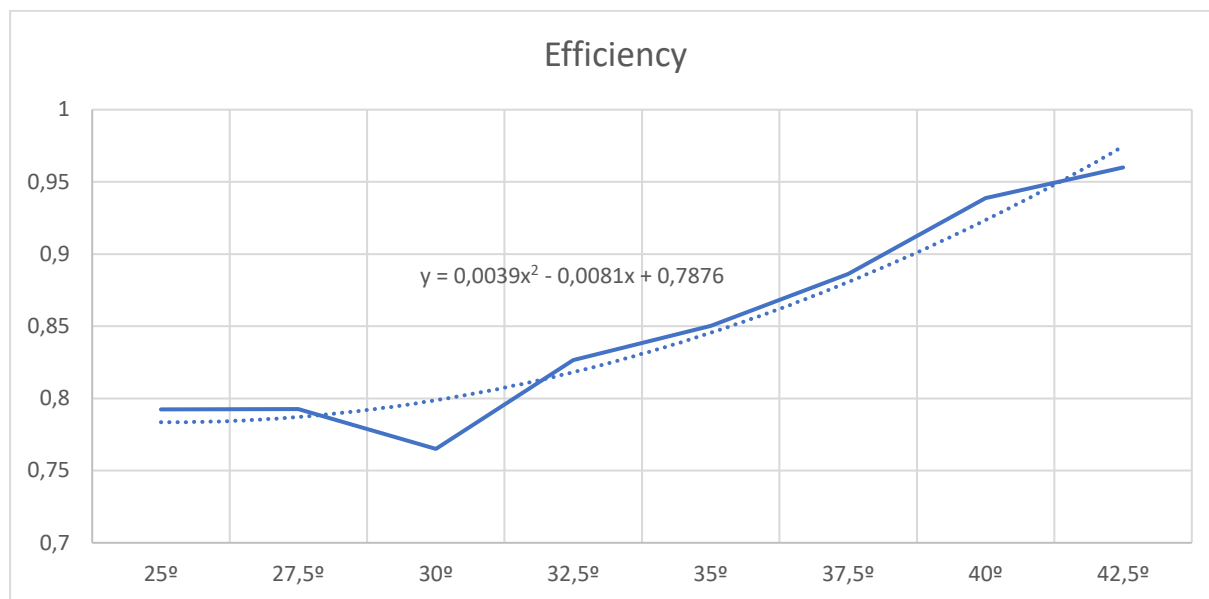


Figure 29. Variation of efficiency as function of water recovered temperature

In above picture is represented the efficiency of exchange as function of clean water outlet temperature from heat exchanger; differences are so small that little differences in decimals can change final results of efficiency.

This means that any decimal error in monitoring can affect calculation of performance. It can be evidenced how efficiency is consistent between 80 and 90%, with increasing tendency for temperature of water closer to temperature of sludge.

Next chart illustrates variation of exchanged power with respect to water outlet temperature.

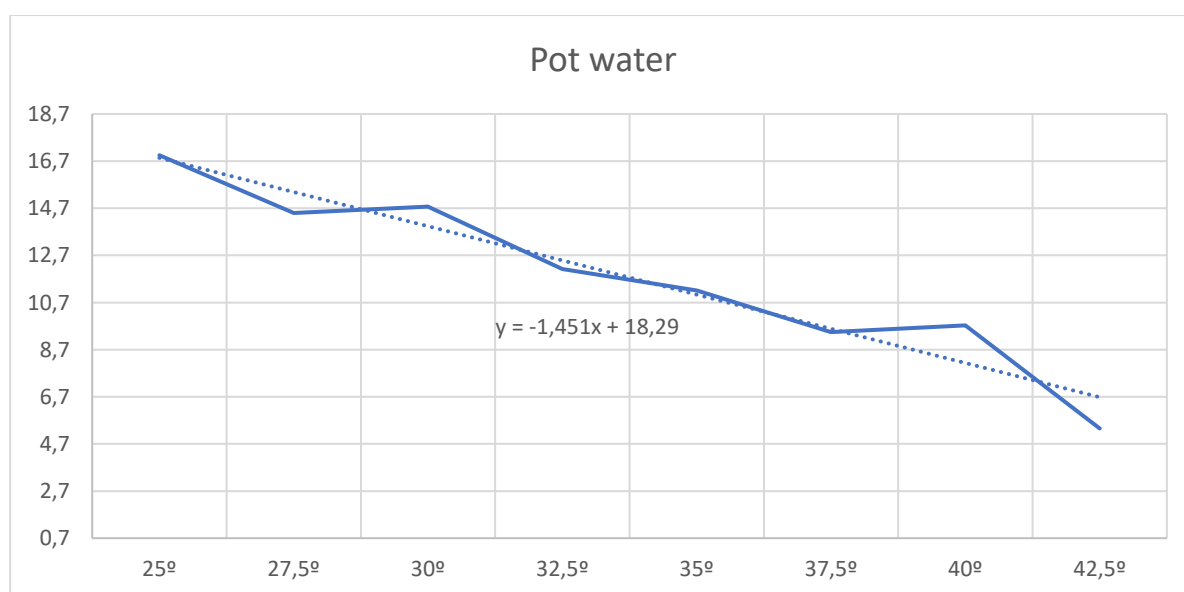


Figure 30. Variation of exchanged power (kW) as function of water recovered temperature

In this case, it can be seen how increment of power is proportionally incremental when temperature of water is “far” from temperature of sludge.

With respect to operation with sludge at 80 lt/m, it could only be achieved in stationary conditions for a relevant period at P&P, where fouling problems were not present (event happened at WWTP).

Here below is represented one part of this point of operation:

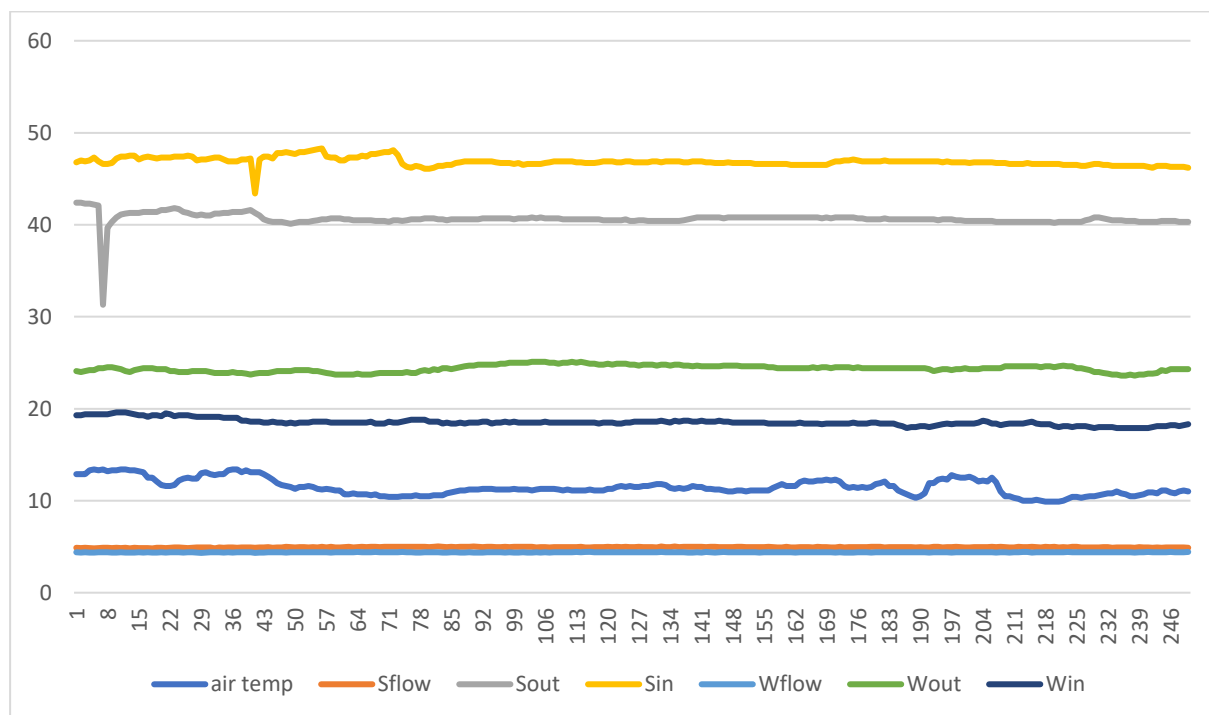


Figure 31. Stable operation at 80 lt/min at P&P factory

Here below the calculation of performance at above point of operation:

Sflow	Sout	Sin	Pot Sludge	Wflow	Wout	Win	Pot water	Eff	Tset
4,948	40,555	46,702	35,484	4,392	24,441	18,346	30,933	0,839	25°C

Table 9 Working point at 80 lts/min

## 6 Problems encountered during operation of HReX

During tests, most of faced problems were related with auxiliary components of skid, automation and other issue related with demo sites.

### 6.1 Corrosion

P&P factory has demonstrated to be a really aggressive environment, especially when effluent exits from the factory and arrives to local WWTP for depuration; vapor created by effluent at medium temperature (around 50°C) resulted to be corrosive for all elements not in stainless steel.

Most of time skid was downdraft with respect to decantation pool, so wind was blowing vapors toward skid, that was evidently unprepared for this kind of boundary conditions.



*Figure 32. Exposure of skid to corrosive vapors of decantation pool*

As consequence, due to prolonged exposition, the weakest elements like electronic components, sensors and copper terminals suffered problems of corrosion, which led to replacements of:

- Embedded pc inside cabinet
- In/out plc modules inside cabinet
- Plc processor
- Water temperature sensor mounted on piping

As consequence, monitoring during period affected by corrosion was not consistent and had to be discarded. New plc and embedded pc required to be programmed and commissioned again, to verify correct communication with remote and automatic operation. At same time, electric cabinet was sealed on the bottom, where all cables enter, in order to reduce infiltration of vapors.





Figure 33. Replaced electronic elements for corrosion

Other parts of skid were affected by exposure to aggressive element, but without compromising operation of the system, so no substitution was required. Nevertheless, thinking to extended period of time, other solution should be found to preserve the integrity of the system; the HReX is the element that presented more reliability and robustness, but auxiliary devices could suffer tremendously and generate undesired stops to installation.

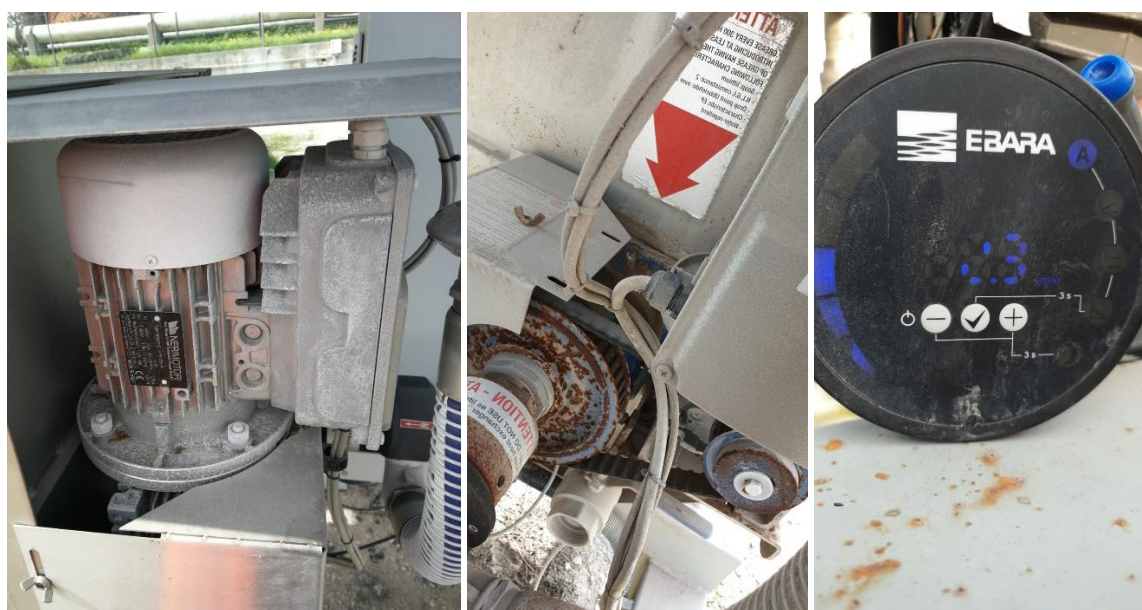


Figure 34. Devices and components affected by vapor corrosion

Finally, also VSD of drycooler was affected by problems related with grounding because of corrosion, event which pushed to dismiss the unit from operating.

Different cause but similar results was detected in Madrid demo, where clean water loop was filled by local team with water used at WWTP for daily operation of cleaning or other activities of maintenance; this kind of water proceed from plant network that reuse depurated water taken from last pool of depuration process, so is free from suspended organic components but has not same characteristic of TAP water from network of municipality.

The result was a corrosive process that affected the coil of drycooler, creating leakages that required the entire substitution of that part of ventilating unit. In below image can be seen on of many leakages detected during filling of water loop, after replacement of water pump broken previously.



Figure 35. Leakages of drycooler water coil



## 6.2 Collision

P&P factory dispose of a “bridge” that is moving along the length of the pool itself; during different inspections with factory personnel , before installation, it was agreed together final position of the skid, in order not to interfere with plant processes, being in a comfortable position for maintenance and protected by possible moving element (like the bridge).

Nevertheless the skid, which was supposed to be placed properly by plant personnel, was object of collision with the bridge a first time, as it can be seen in below image.



*Figure 36. Skid after collision*

Collision caused different structural problems, but not operative; the skid dropped off from its basement, losing necessary horizontal level, while return piping and sludge pump bearing structure suffered deformations.



*Figure 37. Mechanical damages of skid*



The skid was relocated at requested horizontal level, by plant maintenance personnel, but moved backward with respect to initial position, in a position supposed to be safe and away from moving bridge.

Nevertheless a second collision occurred, again without affecting functionality of the skid, but deforming mechanical elements, which required to be fixed. And the unit re-located.



Figure 38. Skid after second collision.

Similar event of collision, but for undetected causes happened in Madrid at WWTP, where clean water circulation pump suffered a fatal damage for collision, which broke the case holding electric motor over pump body, as it can be seen in below image.

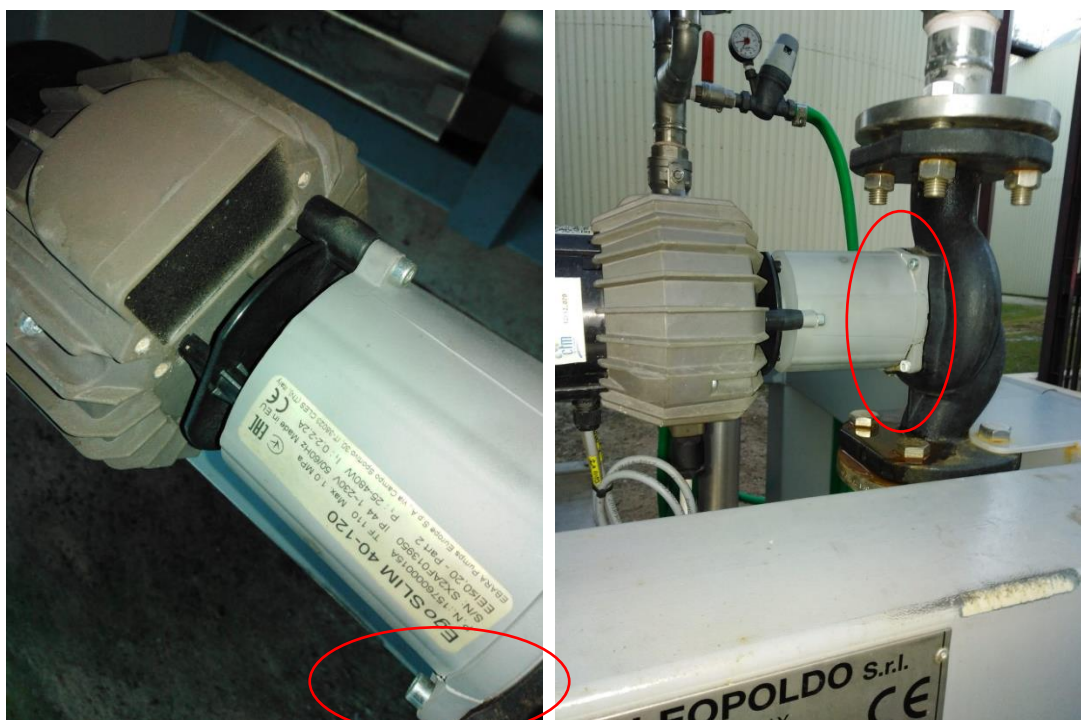


Figure 39. Broken pump for collision effect.

## 6.3 Operation

Inconsistency of most test points at 80 lt/min depends mostly of physical problematic (corrosion and collision) encountered during long term operation, which caused a lot of stops and delays in execution, but also depended by:

- permanent drop pressure of water loop, due to constant presence of air in the system, at P&P
- flow regulation of sludge, due to fouling at inlet piping from digester, at WWTP

Air purge for HReX at P&P is the most problematic commissioning activity faced for this technology, which is robust, reliable and efficient; nevertheless its structure based on lenticular rotating discs, with clean water circulating inside, creates air bags inside upper part of each disc, which are installed in the bottom part of the skid.

The presence of one air bleeder installed on upper manifold of drycooler resulted to be insufficient for this skid solution, so process of filling and purging has been repeated different times during commissioning, but had to be repeated different times along normal operation because never successful at 100%.

Furthermore the incoming temperature of effluent at 50°C facilitate the evaporation of clean water when pressure is below one bar, increasing air presence inside loop, creating cavitation in the pump and interruption/distortion in the flow.

Refilling tans is not especially easy at P&P factory because the skid is away from any TAP water installation and the factory pretended to use own fireman truck for executing the operation, so speed in restoring the pressure of skid was conditioned by fireman availability.



Figure 40. Water loop filled by fireman truck

At WWTP a manual valve, whose opening determines the quantity of flow passing to the HReX, regulated sludge inlet flow. Once the valve was set on a specific flow (with margin of tolerance), the position should have been maintained until next set of working points; the flow could be maintained for 1 or 2 days before dropping to useless limit.

First proposed solution was more opening of the valve, until detecting a flow with enough head to avoid fouling inside piping; this solution was not feasible for the flow required because of the extreme density of the sludge.

Second solution included the integration of filling connection for using plant water to purge fouled piping from solidified sludge; this meant realizing weekly maintenance of unit with local personnel for having batch operation. As results availability of maintenance team effected operation of unit.

## 7 Conclusions

As mentioned in the document, for HP it has been necessary to repeat operation over few operation points due to instability of the system.

Special mention is for operation with condenser outlet temperature at 80°C and evaporator inlet temperature of 45°C with 100%, 75% and 50% of unit capacity; control system of expansion valve during these tests was set on manual mode, with opening between 75% and 85%.

This kind operation is due to discharge pressure that was close to its limit value, which, with automatic controls (mass-flow and PI), would generate instability inside refrigerant loop, therefore forcing safety shut down of unit.

For most of operation points, water flows in evaporator and condenser had to be adjusted (with respect to nominal flows) in order to achieve expected design increment of temperature ( $\Delta T_{\text{cond.100\%}} = 10\text{K}$  y  $\Delta T_{\text{evap.100\%}} = 5\text{K}$ ).

Some modifications was necessary like: 1) modification of safety parameters for maximum suction pressure (from 14 to 17 bars); 2) modification of maximum and minimum values of sub-cooling; 3) software upgrade integrating new control for expansion valve. For each modification, it has been possible to understand achieved effect through different tests of operation.

With respect to comparison between experimental and design performance values, it can be stated that COP values are lower than expected, in a range comprised between 10%, with exception of following working points: 55°C\_35°C\_100%, 55°C\_40°C\_100% y 65°C\_45°C\_100%.

With respect to HReX, both skid have been tested and operated, showing results of efficiency between 80% and 90% for tested points at 55lt/min for effluent, with maximum recovered power around 16 kW.

Limited tests, at 80 lt/min for effluent, showed capacity of heat exchanger of recovering up to 30 kW with efficiency over 83%. It is expected to achieve similar efficiency for other points, with reducing exchanged power as much as water temperatures get close to sludge temperatures.

With respect to maintenance, corrosion problem for auxiliary components emerged dramatically for this kind of aggressive environments; on other hand, the HReX showed robustness, reliability and efficiency during all events (included collision).

For specific environments it is suggested a preliminary study of all boundary variables that could affect the integration of HReX with other devices (who should require at least same level of resistance), in order to reduce maintenance and so interruption of operation.

For high density sludge, it is suggested the use of specific circulating elements, with sufficient head, that could reduce fouling effect of suspended particles.

Is remarkable the fact that reliability in operation of skid (plug & play solution manufactured for limiting impact at demo sites) was not objective of the project, while operation of HReX in stressed environment was; HReX was able to operate as expected against corrosive and high density fluids.