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Laboratory characterization of a cascade heat pump system with intermediate water loop

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Abstract

To reach the goal of decarbonization, the thermal loads of buildings are being electrified with the use of heat pumps in replacement of traditional fossil fuel boilers. In the European project HAPPENING, a cascade heat pump system has been designed for the renovation of a building originally heated by a gas boiler. Air-to-water heat pumps provide heat to a water-loop which is the source for a water-to-water heat pump used to produce domestic hot water and for different water-to-air heat pumps, located in the apartments, that cover the heating and cooling loads. The system is controlled with a model predictive control which aim is the optimization of renewable energy consumption. The performance characterization of the heat pumps and the system is crucial for the definition of such advanced control. In the "Heat Pumps Lab" of Eurac research, the system has been characterized in two phases. In this paper we present the first step which includes the investigation of the operational limits, the definition of a performance map and the calculation of the system performance. The second step is the dynamic whole system test where the system is installed in three climatic chambers: one for the external unit, one for the water-loop and one for the internal units.

Keywords: cascade heat pump, laboratory characterization, whole system test, water loop ;

1. Introduction

The decarbonization of the thermal load of building is a key factor to achieve the energy and climate targets since the heating and cooling demands cover near the 50% of the heat demand [1]. The heat pumps cover an important role in the transition of the electrification of the thermal load of the buildings and in the decarbonization process [1–3].

The proper design of the heat pump is important for the performance and therefore for the operational costs, confirmed by the evaluation of the monitored data [4]. For example, Li et al. [5] evaluated the impact of the storage volume identifying in 30-40 l/kW the optimal solution. Also, heat pumps are used in a hybrid system with gas boilers [6], thermal or electrical storages, and are coupled with solar energy (solar thermal or photovoltaic) [7,8]. In all these mentioned cases the proper control of the system is crucial for performance. Advanced control strategies can improve the COP in a range of 5 to 20% [9–13].

Introducing the heat pump system in a new building is simpler than in the renovation of a building since the design of the new building is integrated: the thermal loads are minimized, the space of the technical room is dedicated to the system, the distribution circuit is at low temperature and can be supply both heating and cooling loads, and so on. In this case one single stage heat pump can work with a good coefficient of performance. Instead, in the renovation of a building there are several barriers to overcome. A single stage heat pump could not satisfy all the requirements of the renovation.

In literature different cascade heat pump systems are presented where the refrigerant of the first stage exchanges heat directly with the refrigerant of the second stage through an intermediate heat exchanger. The

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main advantage of a cascade heat pump is the possibility to reach high temperatures, with the downside that at low or medium temperatures a single stage heat pump can reach higher COP than a cascade heat pump [14–17]. The system design and control are important for the performance; for example, Le et al [17] show that despite a nominal COP 2.5 at 7/80 the system can perform with a SCOP of 1.4 using a storage, 2.1 with direct heating, and 1.9 with price-based control. In renovation of the building, cascade heat pump systems are able to cover the heating loads thanks to the high temperature.

The cascade heat pump system with intermediate water-loop has been developed in the H2020 project HAPPENING. The system is presented in the Section 2. The proposed system presents different advantages for building renovation:

- i) the distribution temperature is neutral minimizing the thermal losses of heat distribution; in addition, the efficiency is higher than the high-temperature cascade systems.
- ii) the distribution system is not replaced (reducing the renovation investment) with adding the possibility of covering the cooling loads independently for each room. Otherwise, a medium temperature terminal would require the replacement of distribution piping (due to a different nominal flowrate) or the change of distribution layout (with a three-pipes or four-pipes distribution).
- iii) in summer the domestic hot water demand can be balanced with the space cooling demand.
- iv) the source heat pump can be decoupled to the heat pumps that cover the loads.
- v) the storage can be manged to guaranty flexibility.

The advanced controllers can improve the system performance acting in these last two points. On the other hand, such systems require a higher investment cost. Therefore, the performance and those features should be guaranteed to justify the cost of such systems.

In the HAPPENING project, the system is installed in case studies and this paper presents the laboratory characterization of the same system in a smaller scale. This activity is used to validate the model used to develop the model predictive control [18]. The methodology for the laboratory characterization is presented in Section 3 while the results of the test on the heat pumps are presented in Section 4.

2. Description of HAPPENING cascade heat pump system

The cascade heat pump system developed with the HAPPENING project has been designed for the renovation of buildings originally heated by a gas boiler. The distribution system of the building is maintained while the generation system and the heat emission terminals are replaced by heat pumps. The system includes air-to-water, water-to-water and the water-to-air prototypes developed by Innova within the project. The heat pumps have different refrigerants: the air-to-water and the water-to-water have R32, while the water-to-air R290. The selection of refrigerants followed the phase down foreseen by EU F-Gas Regulation. In the Heat Pumps Lab of Eurac Research, the HAPPENING system has been reproduced in a smaller scale than the system designed for the demo case. The system considers the same units of the demo case except for the air-to-water that is a commercial unit with R410a already available in the laboratory. The results described in this paper refer to the commercial air-to-water unit and to the prototypes of water-to-water and water-to-air heat pumps.

Figure 1 shows the layout of the system installed in the laboratory. An air-to-water heat pump delivers heat at low-temperature to the water-loop through thermal energy storage. The temperature of the water-loop is controlled by a three-way valve connected to a collector that is the source for booster heat pumps. A water-to-water heat pump is used to produce domestic hot water charging a thermal energy storage while two water-to-air heat pumps control the air temperature covering the heating and cooling loads. The two water-to-air heat pumps are of a different size: the larger one is called WL400 while the other is called WL200.

In Figure 1 there are also identified the hydraulic modules (called energy hubs EH) that the laboratory uses to reproduce the control of the system. The figure reports only the used functionalities of those modules showing with a blue dotted line the control logic. Specifically, the EH7 controls the water-loop temperature, the EH8, EH9 and EH10 control the flow rate of the heat pumps. The EH2 on the secondary circuit simulates the DHW tapping, while in the primary circuit can be configured with different controls: P2 always running or running when there is a tapping, and V2 fully open or controlling the supply temperature.

Differently from the system proposed in Figure 1, the demo case has 15 dwelling and therefore the system presents three air-to-water heat pumps connected in parallel, higher capacities of the buffer and thermal energy storage, and the water-to-air heat pumps are installed in each room of the dwellings.

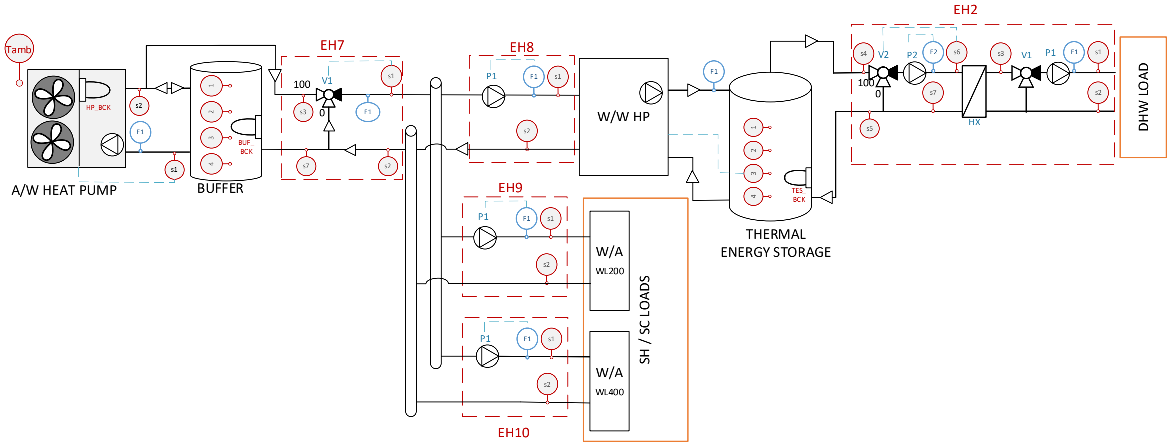

Fig. 1. Layout of the cascade heat pump system

The whole system is tested according to two control strategies: one traditional and a model predictive control. The traditional control is obtained using the heat pumps set point: the air-to-water heat pump controls the return temperature (according to the blue-dotted-line of Figure 1); the water-to-water heat pump controls the storage temperature while the water-to-air heat pumps control the ambient temperature. From the validation of the system model, the model predictive control is developed to optimize renewable energy consumption [18]; than the model predictive control will be implemented in laboratory to control the system. Finally, the system with the model predictive control will be tested.

3. Method

The characterization of the cascade heat pump system was done in two phases:

- Test at component level
- Test at system level

The test at component levels was performed on each unit. The first aim of this activity is the definition of a performance map as a function of the compressor frequency, source temperature and flow rate, and load temperature. Another aim is the comparison of the measurements performed by the laboratory with the internal measurements of the unit in order to validate the algorithms developed by Innova for controlling the performance of the units. Finally, the operational limits of the units are investigated since the demo case can present some boundary conditions out of the nominal and design conditions.

3.1. Test at component level

The heat pumps have been configured according to the instruction of the manufacturer and the compressor frequency has been controlled with different levels.

Table 1 reports the different combinations of test boundaries for the test of the single heat pumps. The boundary conditions considered in the table investigate all the possible operating conditions in order to understand the limits of the units. The choice of the flow rate is explained in the following section for each heat pump.

Table 1. Test boundary conditions at component level.

	Loop Temperature	Load	Flow	Part Load Ratio
W/A – space cooling	10 °C, 17 °C, 25 °C, 30 °C, 40 °C	23 °C, 26 °C	200 l/h, 300 l/h	100%, 75%, 50%, 25%
W/A – space heating	10 °C, 17 °C, 25 °C, 30 °C, 40 °C	19 °C, 22 °C	200 l/h, 300 l/h	100%, 75%, 50%, 25%
W/W – domestic hot water	10 °C, 25 °C, 30 °C	45 °C, 58 °C	1.58 m^3/h	100%, 75%, 50%
	Air temperature	Load	Flow	Part Load Ratio
A/W – space heating	-15 °C, -7 °C, -2 °C, 0 °C, 2 °C, 7 °C, 12 °C	30 °C, 45 °C	1.4 m^3/h, 1.96 m^3/h	100%, 60%, 35%, 20%
A/W – space cooling	20 °C, 25°C, 30 °C, 35 °C, 40 °C	7 °C, 13 °C, 22°C	1.96 m^3/h	Nominal

a) b)

Fig. 2. Installation in laboratory. a) Water-to-air heat pump WL200. b) water-to-water heat pump.

3.1.1. Water-to-air heat pumps

The water-to-air units have a different nominal flow rate corresponding to 480 l/h for the unit WL400 while 240 l/h for the unit WL200. The flow rates indicated in Table 1 are different to the nominal since the demo case is not able to satisfy the nominal flow rate of the unit WL400.

In addition to the points of Table 1, at source temperature of 25 °C and air temperature of 19 °C, the laboratory tested both units at 480 l/h and investigated the minimum flow rate accepted by the unit before presenting faults, warnings, or alarms.

The laboratory has measured the source water inlet and outlet temperatures, the water flow, the internal differential pressure of the source loop, air temperature and humidity, electric consumption and has record the internal registered read by ModBus connection.

In the laboratory installation we recreated a barrier to avoid air recirculation (bypass).

3.1.2. Air-to-water heat pump

The air-to-water heat pump was tested with the nominal flow rate defined according to the EN 14511-3:2018 [19] considering a fixed flow control and nominal condition 7/35 (1.95 m3/h). In addition, some the air temperatures of -15 °C and -7 °C were tested at the minimum speed of the circulator (1.4 m3/h) with the same hydraulic circuit. To measure the different capacities the frequency of the compressor has been limited acting on the internal registers of the unit.

The laboratory has measured the air temperature and humidity, load water inlet and outlet temperatures, the water flow, the internal differential pressure of the load loop, electric consumption.

3.1.3. Water-to-water heat pump

The test of the water-to-water heat pump has been performed with the nominal flow rate defined according to the EN 14511-3:2018 [19]. The load temperature indicated in Table 1 is the supply water temperature where the value at 58 °C has been defined to reach the maximum before presenting faults, warnings, or alarms.

The laboratory has measured the source and load water inlet and outlet temperatures, the water flows, the internal differential pressures, air temperature, electric consumption and has record the internal registered read by ModBus connection.

3.2. Theoretical performance of a cascade system

The equivalent COP of the system composed by two heat pumps connected in cascade, in the hypothetical absence of thermal losses between the exchange from one to the other, can be calculated according to the equation (1). The first heat pump has the subscript "1" while the second heat pump has the subscript "2"; Q is the useful heat, W the electric consumption and COP the coefficient of performance.

$$COP_{syst} = \frac{Q_2}{(W_1 + W_2)} \tag{1}$$

Elaborating the equation (1), the system COP can be described as a function of the COP of the two heat pumps by expressing with energy balances Q and W as a function of COP and source heat.

$$COP_{syst} = \frac{COP_1 \cdot COP_2}{(COP_1 + COP_2 - 1)} \tag{2}$$

The equation (2) is used to evaluate the theoretical performance of the cascade system starting from the COP of the single heat pumps.

3.3. Test at system level

The performance of the cascade heat pump system will be performed with the whole system test procedure PLPE developed by Eurac [20]. The external unit of the air-to-water heat pump is installed in a climatic chamber that reproduces a six-day sequence representative of the year while the hydraulic circuits are installed in another climatic chamber conditioned at internal ambient temperature reproducing the technical room. The water-to-air heat pumps are installed in a calorimeter that reproduces the space heating and cooling loads.

Figure 3 shows the installation prepared in laboratory: in the left part there is the external unit of the air-to-water heat pump; in the middle there are all the components that are installed in the technical room as the internal unit of the air-to-water heat pump, the buffer and the thermal energy storage, hydraulic modules; in the right part there are the two water-to-air heat pumps WL200 and WL400 with the relative pumping hydraulic modules.

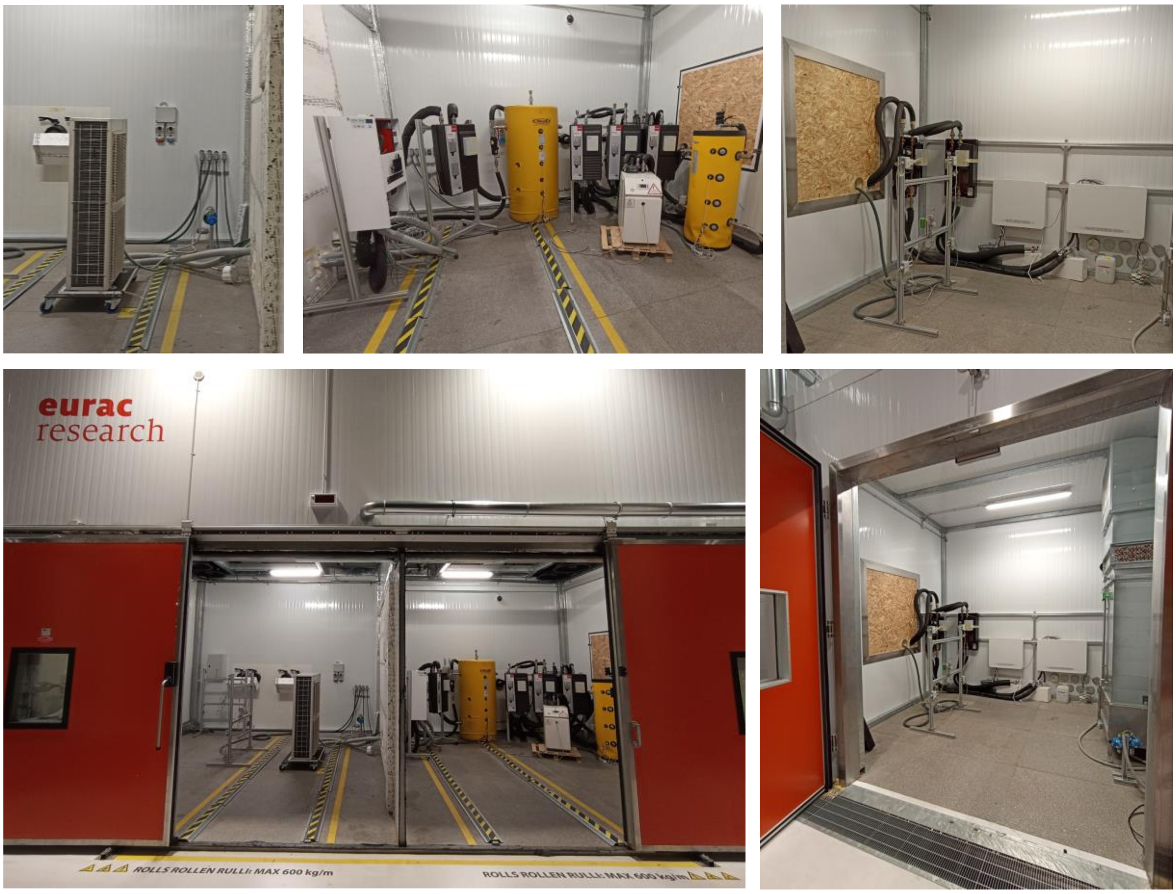

Fig. 3. System reproduced in the Heat Pumps Lab

4. Results

4.1. Test at component level

4.1.1. Water-to-air heat pumps

In order to evaluate the operational limits in terms of source flow rate, in the first stage the two units were installed switching the supply and return piping and in a second moment the installation was corrected. With the wrong installation, the minimum flow rate was varying between 230 l/h and 260 l/h depending to the boundary conditions, while with the correct installation, the minimum flow rate was below 160 l/h.

The request for the demo case is that the unit can work between 200 l/h and 300 l/h even if the nominal flow rate of the unit WL400 is 480 l/h. To verify the effect of the flow rate, a specific test was performed with the water temperature of 25 °C and the air temperature 19 °C controlling the unit according three different capacity levels. Figure 4 shows that the effect of the flow rate is negligible if compared to the effect of variating the compressor speed, but the unit performs better with the nominal flow rate: indeed, the nominal flow rate is higher, and this means a lower temperature difference of the water circuit and therefore a better heat exchange in the evaporator of the heat pump.

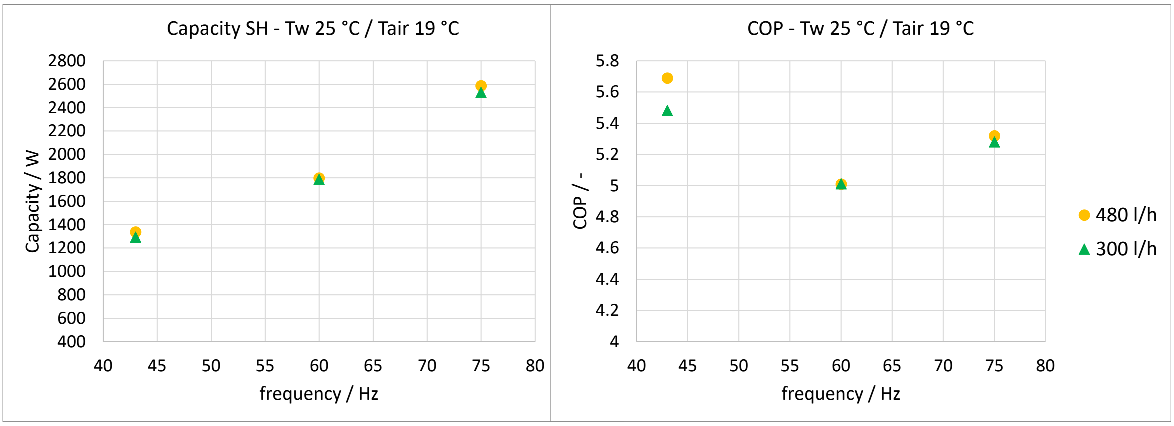

Fig. 4. Effect of source flow rate in the water-to-air heat pump WL400.

The Figure 5 presents all the test points of the unit WL400 while the Figure 6 presents all the test points of the unit WL200. The figures are divided in four diagrams: in the top-left figure it is presented the heating capacity while in the top-right the COP; in the bottom-left figure it is presented the cooling capacity while in the bottom-right the EER. The performance factors are indicated as a function of the source temperature for different series of flow rates and air temperatures. In the capacity graphs it is indicated the frequency of the compressor of one of the four data series.

The operational limits of the units were investigated also in terms of source temperature. The source temperature of 40 °C in space heating as the source temperature of 10 °C in space cooling are not relevant application temperature for a water-to-air heat pump but this test allowed to investigate a wider possibility of the temperature control of the water loop. The COP and EER obtained in those conditions are really high thanks to the very favourable boundary conditions.

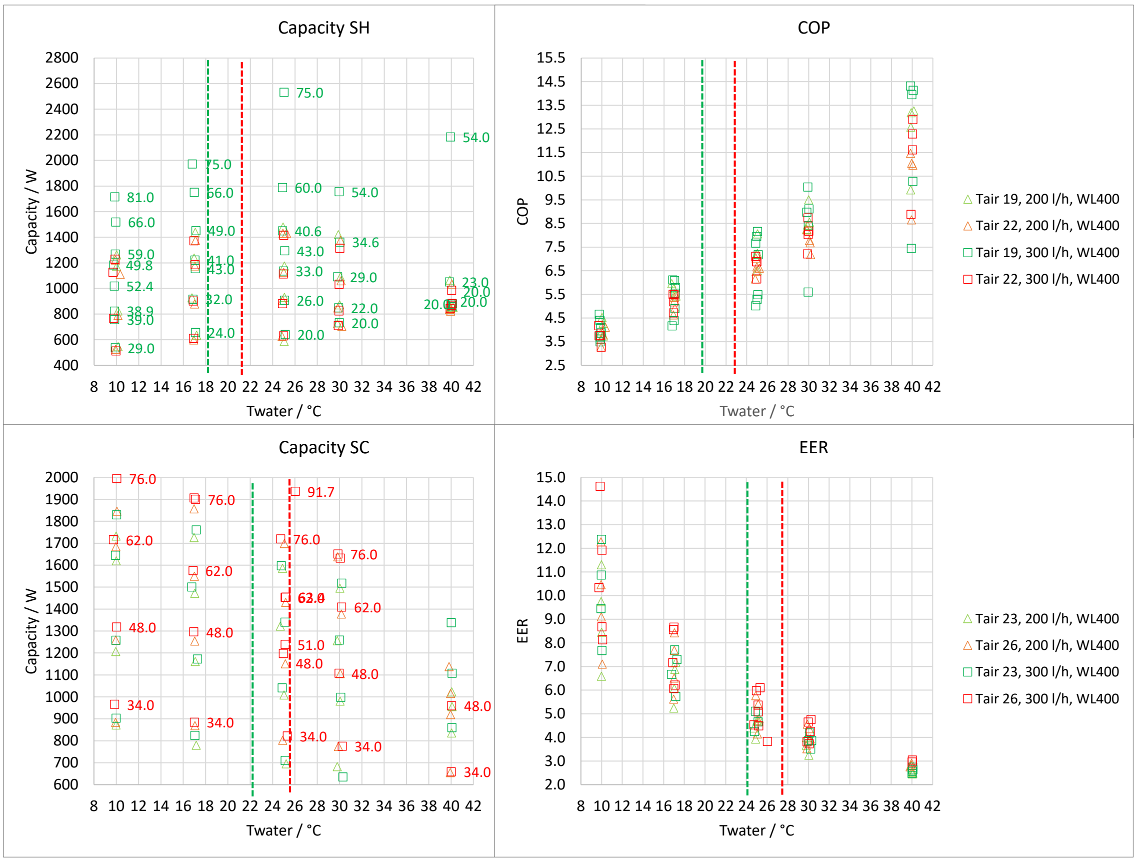

Fig. 5. Performance of water-to-air heat pump WL400.

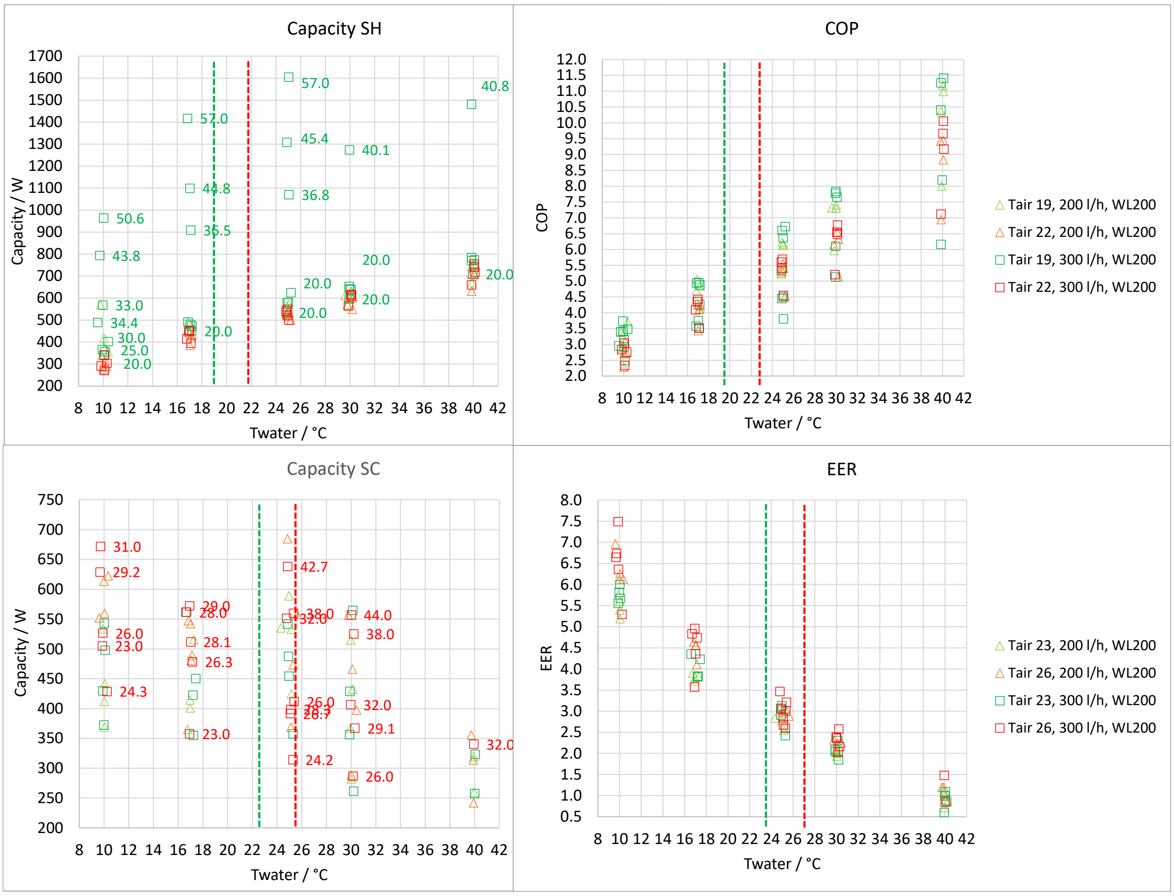

Fig. 6. Performance of water-to-air heat pump WL200.

4.1.2. Air-to-water heat pump

The performance of the air-to-water heat pump presented in Figure 7 shows the heating capacity and the COP according to different compressor frequencies. The limits of the compressor frequency are indicated in one series of the graph. The cooling capacity has been defined only at nominal capacity.

The figure shows the compressor's working range: below 2 °C the compressor does not reach the minimum frequency (since the capacity would be too low) and at 12 °C the compressor is at the top limited due to the high source temperature.

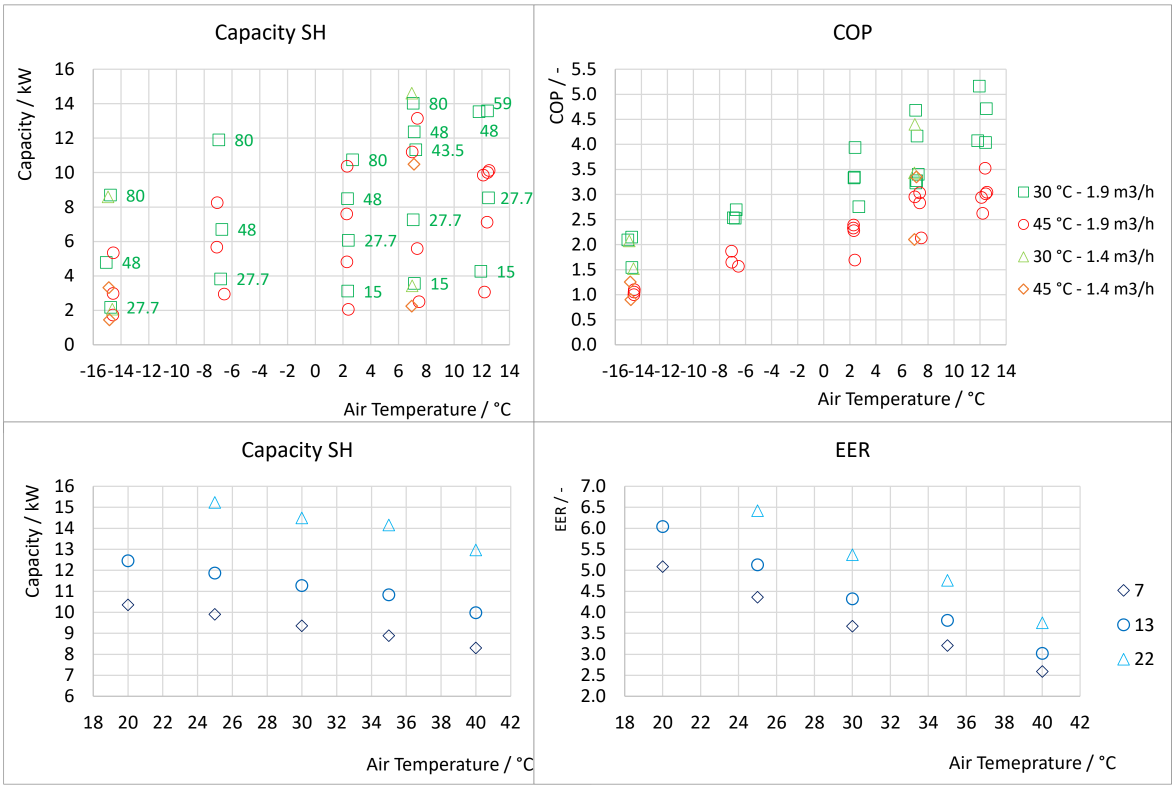

Fig. 7. Performance of air-to-water heat pump.

4.1.3. *Water-to-water heat pump*

The water-to-water heat pump was tested at two load temperatures at supply temperature 45 °C and 58 °C, that was the maximum temperature identified during the test. This limit is higher than the declared maximum temperature.

Usually, the commercial heat pumps for domestic hot water do not provide a modulation in the preparation of the hot water even if the unit has an inverter (that is used during space heating). In the logic of controlling the system with the model predictive control, the water-to-water het pump was tested with PLR of 50 %, 75% and 100%.

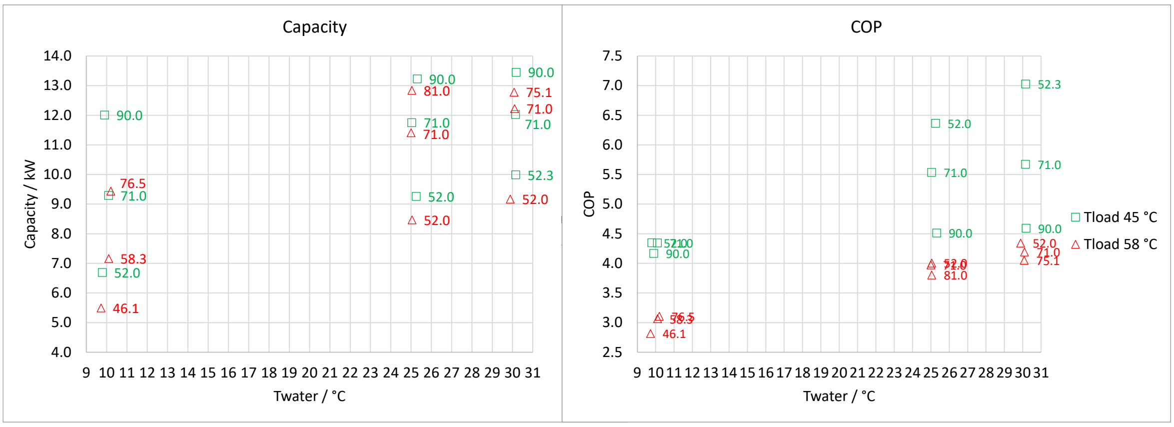

Fig. 8. Performance of water-to-water heat pump.

4.1.4. *Cascade performance*

Table 2 presents the COP calculation of the cascade heat pump system (COPsys) calculated from the COP of the air-to-water heat pump (COPa2w) as source and water-to-air (COPw2a) for the space heating load and water-to-water (COPw2w) for the domestic hot water according to the equation (2). The COPa2w is defined with the air temperature (Tair) and water temperature (Twater loop) corresponding as source/load boundary conditions. The COPw2a is defined from the water temperature to the ambient air of 22 °C. At the same time, the COPw2w is defined considering the temperature of the water loop as source and supply hot temperature 45 °C. The last column presents the COP of the air-to-water heat pump used as single-stage (COPa2w sg) to reach the 45 °C considered as supply temperature for the space heating and the domestic hot water; in this case the COP is not dependent from the water loop temperature. The supply temperature of 45 °C for the space heating is to represent a fan coil as heat emission device to have a similar installation of the water-to-air heat pump.

In the calculation of Table 2 we considered two temperatures of the water loop.

In space heating, the cascade heat pump system performs better than the air-to-water heat pump in single stage for air temperatures up to 7 °C; the only exception is at 12 °C. One consideration is that the second stage works with a lower condensing temperature since the second heat pump works with 22 °C of the air while the air-to-water single stage was supposed to work with fan-coils.

The differences between the cascade heat pump system and the single stage heat pump decreases for the domestic hot water. The motivation is that the boundary conditions are the same since both systems have to heat domestic hot water.

The COP presented in Table 2 are defined at full load and the performance of the cascade system can improve at part load conditions. This motivates the necessity of further investigate on the model predictive controller and the necessity of test in laboratory.

Table 2. Calculation of cascade COP and comparison with a single stage air-to-water heat pump.

Space Heating					
Tair	Twater loop	COPa2w	COPw2a (Tload 22 °C)	**COPsys**	COP a2w sg (Tload 45 °C)
-7	25	3.79	6.87	**2.70**	2.13
-7	35	3.43	8.11	**2.64**	2.13
2	25	4.91	7.07	**3.16**	2.76
2	35	4.45	8.24	**3.14**	2.76
7	25	5.70	6.35	**3.28**	3.21
7	35	5.16	7.15	**3.26**	3.21
12	25	6.62	6.15	**3.46**	3.73
12	35	6.00	7.10	**3.52**	3.73
Domestic hot water					
Tair	Twater loop	COPa2w	COPw2w (Tload 45 °C)	**COPsys**	COP a2w sg (Tload 45 °C)
-7	25	3.79	4.51	**2.34**	2.13
-7	35	3.43	7.03	**2.55**	2.13
2	25	4.91	4.51	**2.63**	2.76
2	35	4.45	7.03	**2.99**	2.76
7	25	5.70	4.51	**2.79**	3.21
7	35	5.16	7.03	**3.24**	3.21
12	25	6.62	4.51	**2.95**	3.73
12	35	6.00	7.03	**3.51**	3.73

5. Conclusions

The performance characterization of a cascade heat pumps system has been performed in the “Heat Pumps Lab” of Eurac research.

The system has been characterized in two phases; the first phase presented in this paper, we investigated the operational limits and have defined a performance map of each heat pump. With this data, we calculated the performance of the cascade heat pump system with intermediate loop and compared the system with a single stage air-to-water heat pump. The results of the detailed performance map obtained in the first phases provided the possibility to the manufacturer to further optimize the units' controllers. The part load performance has been improved to optimize the SCOP; in the water-to-air unit, the manufacturer improved the management of the ventilation and the supply temperature.

The second step of the laboratory characterization will be the dynamic whole system test where the cascade heat pump system is installed in three climatic chambers. In this test we will evaluate a traditional control strategy and the model predictive control developed with the HAPPENING project.

The performance of the cascade system is comparable to the single stage heat pump. Despite the higher cost needed for the installation and similar performance, the cascade system presents several advantages that are optimized with the implementation of the predictive controller: the domestic hot water can be balanced with the space heating during the summer season; the generation part can be decoupled to the loads; the management of the storages (thermal and electrical) guarantees flexibility and renewable energy utilization.

Acknowledgements

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