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Experimental Analysis of Various Refrigerant Circuit Component Combinations for Low Charge Propane Heat Pumps

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ABSTRACT

In the last years the choice of the refrigerant had become more important to fit the F-gas regulations. Natural refrigerants, such as propane, are one option, but e.g. flammability and safety requirements for installation must be complied. 150g refrigerant charge of propane keeps being focused as the critical amount of charge regarding indoor applications.

Taking these 150g of propane as target value for the operating charge, the project LC150 has been started together with a consortium of nine heat pump manufacturers. The goals are the identification of charge and energy efficient components as well as their combination in refrigerant cycles. This has been achieved by concentration on charge efficiency of heat exchangers, compressors, oil and pipes.

A broad experimental cross evaluation of these components was set up, where they are combined into various refrigerant circuits. The results were used to identify charge efficient and thermodynamically efficient components. Additionally critical cycle characteristics were identified. The precisely determined overall refrigerant charge of each circuit has been varied to find an optimal charge of each circuit component combination.

Presented circuits are in the capacity range of 8kW focusing on brine-to-water heat pump systems and using 100g to 260g of propane. The optimal charge for the tested circuits lies between 160g and 200g with a SCOP of up to 5. More charge would not increase the performance. A SCOP of 4.7 could be reached for 150g refrigerant charge.

The methods of charge reduction and the technics of determining the charge are presented as well as some of the available results of the project in terms of heating capacity, COPs, SCOPs, actual and potential refrigerant charge.

Keywords: heat pumps, propane, charge reduction, refrigerant circuit optimization

1. INTRODUCTION

The installation and use of heat pumps are increasing worldwide. In parts of Europe, the heat pump has become the dominant heating solution in new buildings. Due to the increasing awareness towards global warming, the need to reduce the use of fossil fuels and environmentally harmful gases, the market share of heat pumps is expected to rise steeply. Heat pumps use electricity for heating purposes with significantly higher efficiency than pure electrical resistance heaters. Combined with electricity from renewable sources, heat pumps can provide building heating without using any fossil fuels during operation. Currently most heat pump systems employ refrigerants with significant global warming potential (GWP), among others due to security advantages regarding flammability and toxicity. The global community unanimously banned refrigerants with any ODP by the Montreal protocol (United Nations Foundation, 1987) and is now gradually restricting the maximum GWP for refrigerants. In Europe the F-gas Regulation (Official Journal of the European Union, 2014) is implemented to phase out the use of refrigerants with a high GWP. Such regulations encourage and force the shift towards refrigerants with very low GWP values, such as natural refrigerants, in a timely manner. Propane is a well-known refrigerant with excellent thermodynamic properties and a minimal impact on the environment (GWP =3, ODP =0). Furthermore, no regulations, except for safety, are expected to apply for propane as refrigerant, making it predestined for use in heat pumps. Propane heat pump research focuses on developing security systems (C. Sonner, 2017)(Colbourne and Suen, 2014), optimizing performance (Zottl, 2016), reducing charge (Andersson *et al.*, 2018; Palm *et al.*, 2006; Dankwerth *et al.*, 2020; Will *et al.*, 2020) and comparing various refrigerants i.e. evaluating the different perspectives and making comparisons to other, mainly synthetic, refrigerants (Abdelaziz *et al.*, 2015; Hwang *et al.*, 2004; Konghuayrob and Khositkullaporn, 2016). This paper will show the results of a charge-reduced brine-to-water propane heat pump.

2. MAIN SECTION

2.1. Measurements

All measurements presented were taken at Fraunhofer ISE. To ensure standardized testing, conditioning modules, were used to simulate source and sink and are referred to as secondary modules/circuits. These conditioning modules are standardized equipment in the laboratory and have the following adjustable/ controllable parameters: fluid temperature, pressure drop and mass flow. The conditioning module for the sink side is filled with water and the module on the source side with a mixture of ethylene/glycol and water with a freezing temperature of -20°C. For evaluation, the energy fluxes were measured in the following ways. The electrical power consumed by the driver and compressor was measured between the driver and the power grid. Therefore, all frequency converter losses are included. The thermal heat fluxes on the secondary sides were calculated by the measurement of the mass flux employing a Coriolis sensor, combined with in- and outlet temperature measurement, using submerged PT100 sensors. Three similar sets of conditioning modules and PLC's (programmable logic controllers) for sensor recording were available, which allowed three refrigerant circuits to be measured in parallel. To estimate the power necessary for external pumps on the secondary side, differential pressures across the heat exchangers on the secondary side were monitored by pressure differential sensors. Controllers were used to control the inlet temperature by adjusting cooling rate employing the building wide cooling network. The temperature difference between in- and outlet of the two plate heat exchangers on the secondary sides, were controlled by adjusting the mass flows of secondary fluids. The source side was set to 3K

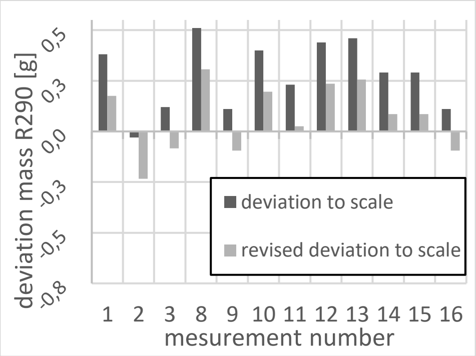

Figure 1: Comparison of accuracies between the charging station and a scale; transported R290 varies between 10g and 60g

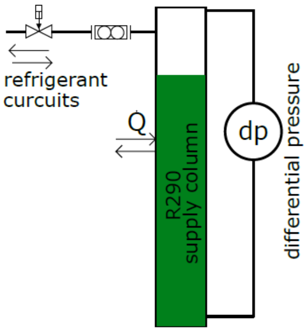

Figure 2: Working principle of the charging station (simplified), the heat flux is designed to be bidirectional.

and the sink side to 5K temperature difference within the secondary fluids. The suction-side superheat of the refrigerant circuit was controlled with an electric expansion valve.

All measurements relied on adjusting the charge employed to the refrigerant circuits. For this purpose, a special charging station was developed and constructed, with the specific task in mind to ensure accuracy, reliability, automated charging and safe discharging of up to three refrigerant circuits in parallel. It is based on two redundant measurement principles, a differential pressure sensor weighing the R290 supply in a column and a Coriolis Sensor detecting the mass flux leaving or entering the supply column. The two sensors fulfill different roles: the Coriolis is tasked with live measurements and determining good estimates of transferred R290, the pressure differential sensor focusses on accurate inventory measurements in the supply column. To control the direction of the R290 flux the supply column can be heated or cooled. A simplified schematic can be seen in Figure 2.

To check the repeatability and precision of the charging station a comparison between the weight measurements of the differential pressure sensor and a laboratory scale was taken. The results can be seen in Figure 1. The revised values were corrected by a constant drift of the scale, due to long measurements periods of the column (45min). The deviation between the two measurements is adequate for the project purposes which leads to a reliable and documented charging process. The transported amount of R290 varied between 60 g and 10 g. The direction of the R290 was always from scale towards column.

2.2. Previous measurements and theoretical connection

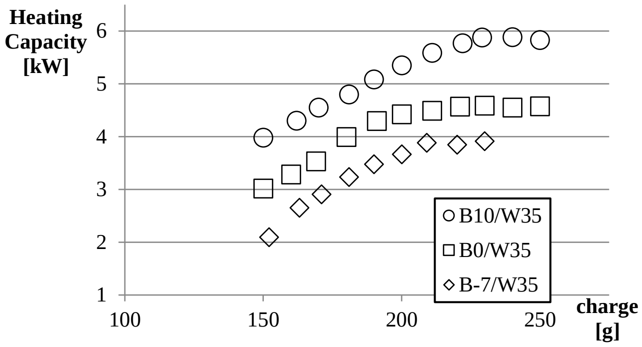

Figure 3: Heating capacity over charge, comparison of different source temperatures with compressor frequency 60 Hz and superheat of 10 K (F60/SH10).

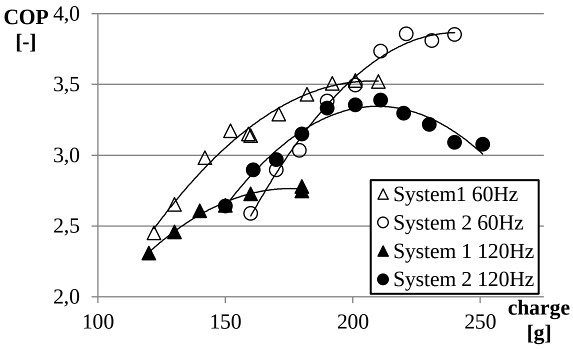

Figure 4: COP over charge graph, comparing two systems. Operation point: B0/W35/SH10.

Premeasurements had shown that a significant heating capacity can be achieved by using 150g of propane as a refrigerant (Dankwerth *et al.*, 2021). During the measurements the impact of charge on the heating capacity (Figure 3) and efficiency (Figure 4) was evaluated. In all measurements the heating capacity reaches an area where it is stagnating with increasing charge. The efficiency is reaching its maximum in the stagnating area of the heating capacity and is therefore called “minimum efficient charge” in the following. Operation with lower charge than the minimum efficient charge is not recommend, as the controlling of the heat pump via expansion valve is not possible. For operation points with smaller charges than minimum efficient charge, the expansion valve is fully open. This leads to higher superheat than stated in the legends.

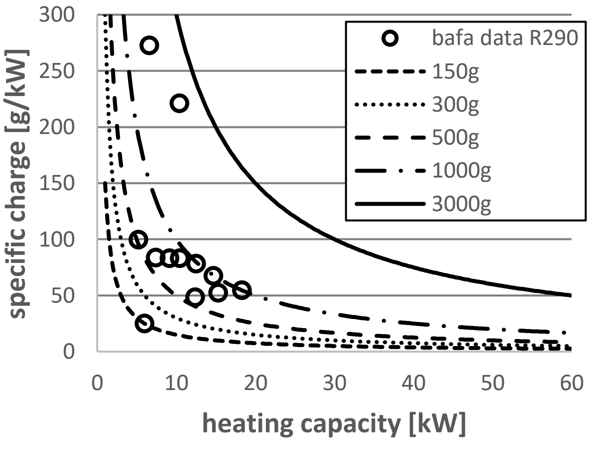

Figure 5: BAFA data from 2021 for brine to water heat pumps with R290.

Figure 5 shows all brine to water heat pumps running with R290 registered in the BAFA list from 2021 (German subsidy register). The charge of most systems is between 500 and 1000g of Propane for heating capacities up to 20kW. Only one heat pump is available with a charge of 150g.

The overall goal of the project is to evaluate and predict the minimum efficient charge, in brine to water refrigerant circuits. The heat pump needs to be designed to fall below the constant charge line of 150g in Figure 5. Depending on sink or source temperature variations, on compressor frequencies and superheat the minimal amount of refrigerant the minimal efficient charge varies. Since SCOP (Seasonal Coefficient Of Performance) represents all most operation states, the minimum efficient charge for the most charge intensive SCOP must be determined. All other operation points (A-F) need to work with that charge. This represents the minimal amount of refrigerant the heat pump can work with to achieve an acceptable or competitive SCOP. Information on performance for a charge of up to 260 g was collected to identify among others the maximum heating capacities independent of the charge of the circuits.

3. SET UP OF PROTOTYPES

All prototypes measured by Fraunhofer ISE were built as the flow chart in Figure 6. The refrigerant circuits were built in the workshops at Fraunhofer ISE, manufacturing guidelines are coordinated with partners in the project´s advisory board.

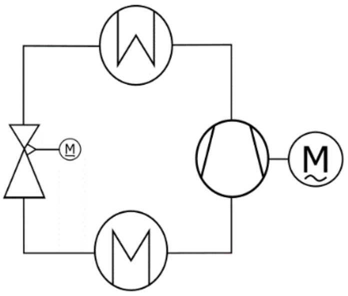

Figure 6: Simplified flow chart of refrigerant circuit

The following analysis focuses on 4 prototypes. The components used were all selected to be able to provide 8kW heating capacity in their upper rating range. A list of the later shown refrigerant circuits is available in Table 1, including piping information. The piping information is coded in, discharge line = DL, liquid line =LL, injection line =2pL and suction line =SL. Generally, all pipes were insulated by 1cm foam insulation. More in-depth information on the used components can be found in Table 2, the information, on the plate heat exchangers, is all relative to ensure animosity of the manufacturers. Similar measures were taken for the compressors by classifying them into groups of compression volume.

Table 1: First refrigerant circuits for cross evaluation

Prototype	Condenser	Evaporator	Compressor	Pipe_d.-outer DL/LL/2pL/SL [mm]	Pipe-length DL/LL/2pL/SL [mm]
RC81	Cond-8-a	Evap-8-a	Comp-C-a	12/12/12/16	480/190/160/900
RC82	Cond-8-b	Evap-8-a	Comp-C-b	12/12/12/12	810/200/200/810
RC89	Cond-8-b	Evap-8-a	Comp-C-b	12/12/12/18	810/200/200/810
RC86	Cond-8-a	Evap-8-f	Comp-C-a	12/10/12/16	500/150/150/320

Table 2: Selected components for first cross evaluation

Plate heat exchanger	Plates [-]	Hight [m]	Width [m]	Profile [-]	Material [-]
Cond-8-a	36	h	w	Dimple	Stainless Steel
Cond-8-b	46	0.80h	0.60w	Fishbone	Stainless Steel
Evap-8-a	20	1.30h	1.20w	Dimple	Stainless Steel
Evap-8-f	40	0.98h	1.06w	Dimple	Stainless Steel
Compressors	Category [ccm]	Compression [-]	Oil (reduced) [ml]		Material
Comp-C-a	25-30	Scroll	400		Steel
Comp-C-b	25-30	Rotary	200		Steel

3.1. Basic operation point and measurement envelop

To be able to compare all components and prototypes equally, a common operation state were defined. Brine to water heat pumps are inter alia measured at B0/W35 with no specification towards load percent or super heat. This gives significant room for adjustments. Based on this combination of temperatures B0/W35 was used as baseline; the quantifications, 40% rpm of range plus minimum rpm (depending on compressor) and 10K superheat were added to give a complete set baseline for all measurements. All parameters are varied individually from these values. Except for some specific extreme point combinations where multiple values deviate from the baseline. For a global comparison, SCOP were selected as the primary evaluation criteria. Figure 7 shows the COP development over charge for a refrigerant circuit (RC). The black diamonds represent the final SCOP of the RC. Based on the measurements, 180g is regarded as the minimum efficient charge for RC89, shown in Figure 7. The measured operation points are similar to EN14825.

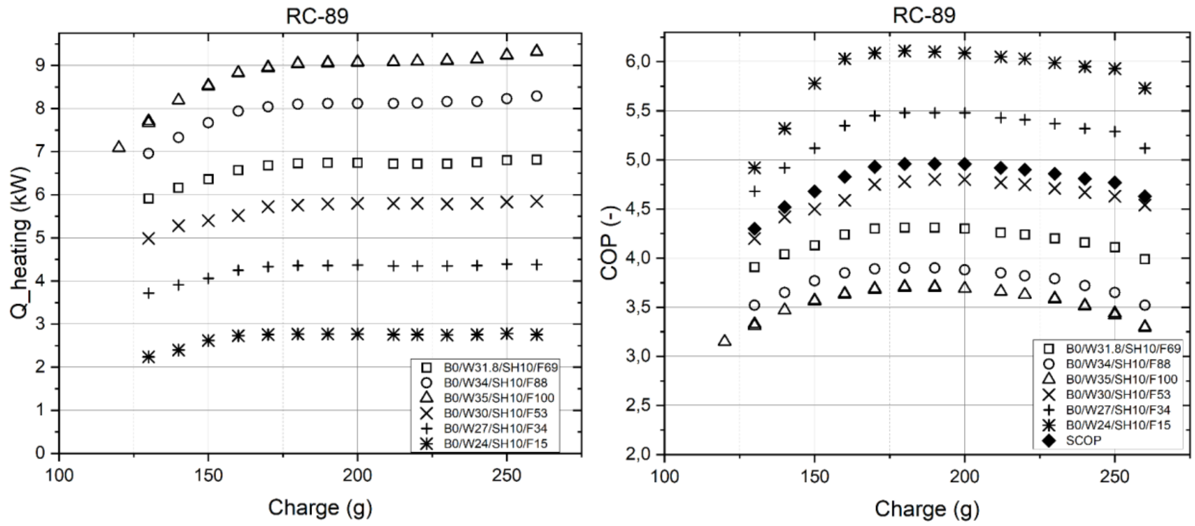

Figure 7: Heating capacity and COP over charge for SCOP operation points, measured for RC89

Refrigerant charge has a significant role in the performance of a heat pump; therefore, all varied operation parameters were measured for a wide range of charge. The measurements were started with as little charge as possible for stable operation and charge was added successively, in 10g increments, until security shut of occurs. During every charge increment, all points of operation were measured if possible. When running measurements, which approached shut of criteria, the measurement was skipped, and a relaxation period was executed before attempting the next planned measurement. All varied parameters add up to 20 individual measurements per charge increment and can be found in Table 3. Considering the charge increments every RC were measured for about ~300-400 operation points. This procedure will be applied to all future measurements.

Table 3: Variation of parameters for measurements

Charge [g]	Super heat [K]	Source Temp [°C]	Sink Temp [°C]	Rpm [%]	Special points [-]
0 – 300	5/10/15	-7/0/10	24/27/30/34/ 35/45/55/65	10/40/70/100	B10-W65

All measurements, evaluating calculations and refrigerant charging operations were done fully automated, to increase reliability as well as speed in the measurement process.

4. MEASUREMENT RESULTS

Preliminary results of three RC's are shown below (Figure 8/ Figure 9/ Figure 10). These three figures have been selected to show the behavior based on charge and one variation parameter.

4.1. Variation of super heat

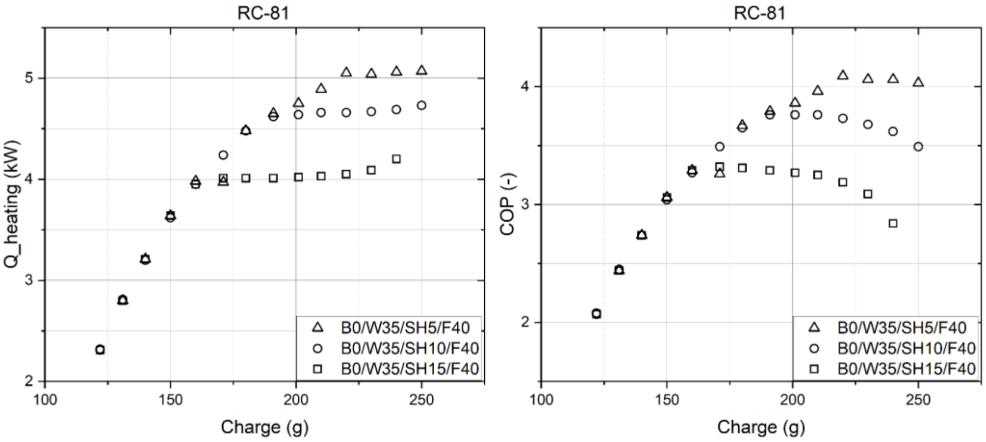

Figure 8: Heating capacity and COP over charge of RC-81 in dependence of superheat

As seen in Figure 8 super heat has a very strong impact on the minimum charge needed for efficient operation. The minimum efficient charge for heating capacity is higher with decreasing superheat. On the other hand, the minimum efficient charge is reached at lower charges for higher superheat values. In the second figure the change in COP is plotted over the total charge in RC81. The maximum reachable COP decreases with higher superheat. For a given configuration this illustrates the optimization problem between low charges and higher efficiencies. This is significant and will have to be considered in all further measurements and optimizations.

4.2. Variation of the sink temperature

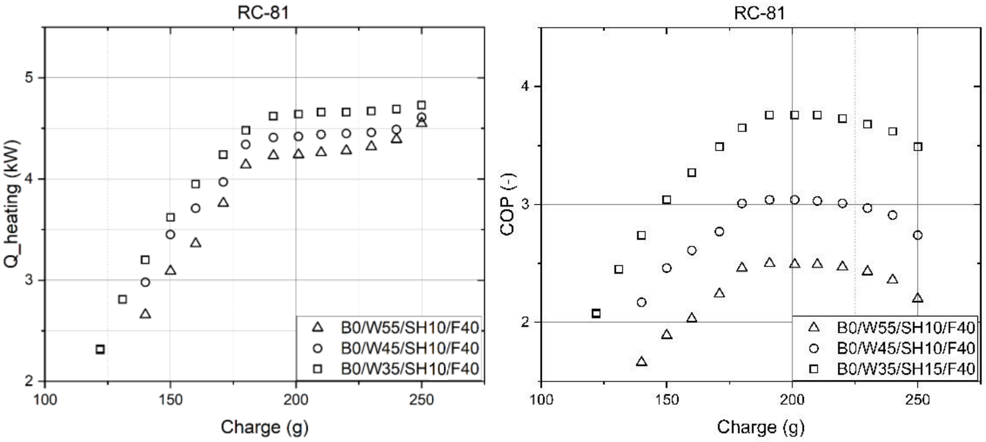

Figure 9: Heating capacity and COP over charge of RC-81 in dependence of the sink temperature

The Figure 9 shows the heating capacity and COP development over charge with varying sink temperatures. For the heating capacity there is no significant impact visible, compared to other parameter variations. Higher sink temperatures lead to slightly lower heating capacities. The different sink temperatures have a strong impact on the COP of the system: the higher the sink temperature the lower the COP.

4.3. Variation of the source temperature

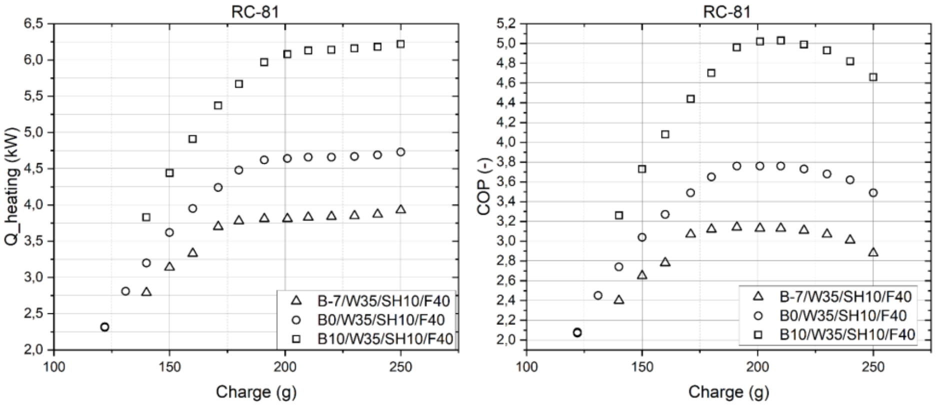

Figure 10: Heating capacity and COP over charge of RC-81 in dependence of source temperature variation

The source temperature variation is shown in Figure 10. Lower source temperatures cause to lower minimum efficient charge values (175g for B-7; 185g for B0; 200g for B10). This connection to source temperature is not necessarily useful when designing a heat pump since the source temperature cannot easily be adjusted, nevertheless it is an existing influence and is of significant importance when considering future nontraditional heat recovery applications. Additionally, the figures show the lower the source temperature is the lower are the heating capacity and COP.

4.4. Comparison of different refrigerant circuits

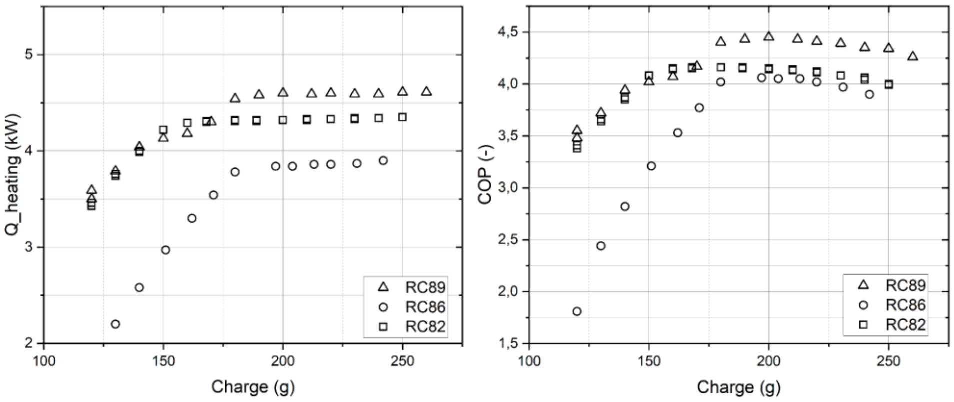

Figure 11: Comparison of different refrigerant circuits at same operation B0/W35/SH~10K/F40

Figure 11 shows the heating capacity and the COP over charge for three different refrigerant circuits (RC89, RC86 and RC82) as shown in Table 1. The different configurations of components have a high impact on an adequate charge of the system. The RC86 reaches the minimum efficient charge at 180 g with much lower heating capacity but similar COP than RC82. RC86 differs in compressor, evaporator and condenser compared to RC82/RC89 with strong effect on the behavior of COP reduction for lower values than the minimum efficient charge value. RC82 and RC89 show a much smoother and flatter decrease for values below the minimum efficient charge values of 160 g and 200 g, respectively. Even though the configuration RC82 and RC89 differ only in suction line pipe diameter, for a refrigerant charge higher than 170 g heating capacity the COP differ significantly with preferable values for RC89. Strong attention has to be given in under-sizing the pipe diameters.

5. CONCLUSIONS AND OUTLOOK

As seen in the measurements individual components have a significant impact on the performance while changing operational conditions and refrigerant charge in the system. Current best performing refrigerant circuit is achieving an overall SCOP of 5 with a minimum efficient charge of 180 g and a maximum heating capacity of 9 kW. This leads to a specific charge of 20 g/kW. A reduction of charge to 150 g results in a SCOP decrease to a value of 4.7. Both results reinforce the implementation of efficient refrigerant circuits with reasonable heat capacities and significant charge reduction compared to market available heat pump configurations.

Different impacts on COP, heating capacity and minimum efficient charge were analyzed in this paper. Operation with lower charge than the minimum efficient charge is critical due to the limitation of controlling via expansion valve for these operation points; the expansion valve is fully open for these points. The variation of superheat from 5 K to 15 K results in one of the refrigerant circuits in a decrease of maximum COP of 0.7 and a shift of minimum efficient charge from 220 g to 160 g. Variation of sink temperature has hardly any effect on the minimum efficient charge; however, as well known, an increase in sink temperature yields lower COPs; up to 0,5 in the analyzed circuit. The variation of source temperature shifts the minimum efficient charge by ca 20 g to lower values for lower temperatures.

The outlined operation states of the cross evaluation cover a wide range of operation and are designed to enable component focused variation of all parts of the heat pump. The wide range of variation parameter will enable the analyses of the impact of each individual component on the overall heat pump. The planned measurements include 20 or more different components which will be built into prototypes, which enable Fraunhofer ISE to evaluate them appropriately until the end of the project in 2023.

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