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THEORETICAL ANALYSIS FOR CHARGE REDUCTION IN A 200 KW HYDROCARBON HIGH TEMPERATURE HEAT PUMP

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ABSTRACT

Hydrocarbons with thermodynamic properties similar to synthetic fluids are alternative working fluid for high temperature heat pumps without the negative environmental impact of greenhouse gases. Though hydrocarbons have good performance as a working fluid for high temperature applications, they are constrained by high flammability. Hydrocarbons such as butane also have a high cost per kg. This study theoretically evaluates the opportunities to reduce the charge of a 200 kW hydrocarbon high temperature heat pump module that is designed for industrial applications. The theoretical analysis is based on an experimental test facility for component sizing references and design alteration possibilities. A charge reduction of 50 % was achieved from the analysis. By optimizing the design for charge reduction, an equivalent charge to the reference model has a 12.6 % increase in COP.

Keywords**:** Charge optimization, Cycle improvement, Natural working fluids, Hydrocarbon safety

1. INTRODUCTION

A 20 kW high temperature heat pump model was built to develop, evaluate and demonstrate the potential of using natural working fluids for high temperature heat delivery by the recovery of waste heat. Propane and butane are hydrocarbons that have similar thermodynamic properties and performances to synthetic fluids (Hydroflorocarbons HFCs and Hydrofloroolefins HFOs). This high temperature heat pump (HTHP) will deliver heat above 110 ºC suitable for process applications such as distillation, drying, pasteurization sterilization and many others (Bamigbetan *et al.*, 2016, 2017a, 2017b). It will replace existing capacities of low-pressure steam boilers and direct electric heating.

Safety considerations have become more important recently in the selection of working fluids for heat pump systems. Fluids will have to meet both the requirements for long-term negative impact on the environment and the immediate dangers of the fluid to equipment and human lives (Clark & Wagner, 2016; Hoglund-Isaksson *et al.*, 2017). While hydrocarbons have zero ozone depletion potential (ODP) and negligible global warming potential (GWP), they are classified as 'A3', implying high flammability with low toxicity. The flammability property of these working fluids have to be considered in the development of heat pumps with hydrocarbons.

For industrial applications, with capacities above 200 kW, the charge of working fluid in the heat pump system will be high. Hydrocarbons such as butane (R600) have a relative high cost (670 NOK per kg) when compared to other working fluids. A high cost of working fluid will potentially increase the investment and maintenance cost of the heat pump. The savings gained by a more efficient energy system will be reduced if the cost of its operation with butane is high.

The flammability of hydrocarbons and the high cost per kg of butane are two important drawbacks to the implementation of the HTHP with hydrocarbon working fluids. This study conducts a theoretical analysis of the opportunities for charge reduction in a cascade propane – butane HTHP. The study evaluates the experimental results of a model HTHP and develops solutions to minimize charge within the system. Using the test facility as a reference model, a theoretical analysis is conducted for the opportunities to reduce the hydrocarbon charge while improving the system performance. The analysis is scaled and theoretically implemented to a 200 kW HTHP for industrial applications.

Since the discovery of the harmful effects of synthetic working fluids, many researchers have investigated the various ways to reduce the charge within a heat pump system. Their studies consisted of varying configurations of heat pumps, different working fluids and component sizes. Some focus are on small capacity refrigeration, air conditioning and heating systems (Bjork & Palm, 2006; Cho *et al.*, 2005; Kim & Braun, 2012; Palm, 2007; Saravanan *et al.*, 2017; Wu *et al.*, 2012), others focused on micro channel and compact heat exchangers (Hrnjak & Litch, 2008; Kheiri *et al.*, 2011; Park & Hrnjak, 2008). Several studies have evaluated charge reduction strategies from a broad perspective (Cavallini *et al.*, 2010; Vaitkus, 2011). Governing bodies have set standards and regulations that further ensures that future development of heat pumps will require minimal charge of fluid. In 2014, the International Institute of Refrigeration released a note on refrigerant charge reduction in refrigerating systems. The note evaluated charge distributions and made recommendations to minimize charge (Poggi *et al.*, 2008).

2. THE OPPORTUNITIES FOR CHARGE REDUCTION

The distribution of charge between components of a heat pump can give an insight into the opportunities for charge reduction. Additional charge of working fluid in some components may not result in a more efficient heat pump. The charge per component can be optimized to what is required for the best performance of the heat pump, even at off design conditions. Component sizing also affects the amount of charge required. A larger volume than necessary will require more working fluid charge for equivalent performance.

Table 1: Charge distribution within the heat pump for the 20 kW capacity test facility and the 200 kW capacity simulation

200 kW Theoretical distribution					20 kW test facility. Estimated		
Component	Fluid	Volume (L)	Average Mass (kg)	% mass	Volume (L)	Average Mass (kg)	% mass
Condenser	R600	31.3	3.53	22.1	1.9	0.66	13.5
Cascade HX	R600	25.0	0.41	2.6	4.3	0.08	1.6
Cascade HX	R290	25.0	3.22	20.1	4.3	1.02	20.8
Evaporator	R290	18.8	0.43	2.7	1	0.04	0.7
HPR HTC	R600	20.0	3.63	22.7	4.4	1.11	22.7
HPR LTC	R290	20.0	3.89	24.3	4.4	0.86	17.9
Accumulator HTC	R600	20.4	0.42	2.6	5.8	0.06	1.3
Accumulator LTC	R290	20.4	0.45	2.7	5.8	0.09	1.9
Piping HTC		-	-	-	1.43	0.25	5.0
Piping LTC		-	-	-	1.43	0.24	5.0
HTC (Compressor, lubrication,)		-	-	-	-	0.24	4.8
HTC (Compressor, lubrication,)		-	-	-	-	0.23	4.7

Table 1 shows the distribution of charge across the heat exchangers, storage vessels and other components of the two cycles of the heat pump. The 200 kW theoretical analysis did not consider mass in compressors and pipelines and are assumed to have values independent of heat pump configuration (minimal piping length and lubrication solubility). The heat exchangers and separators on the high-pressure sides have the highest percentage of the total charge. The mass of working fluid in these components represents 89.2 % of the total charge. Working fluid mass in the components of the 20 kW test facility are calculated and in heat exchangers estimated. The total mass in heat exchangers and separators on the high-pressure side of the heat pump cycle is 75 % of the total charge. As shown in the charge per cycle of the test model, the charge is similar for both the HTC with butane (2.4 kg) and the LTC with propane (2.5 kg). The potential for charge reduction will be on the high-pressure sides of the heat pump cycles and is the focus of this study.

There are possibility to reduce the charge in the pipes of the heat pump especially the liquid line (condenser to expansion valve). For the 20 kW test model, the liquid line represents 78 % of the total charge in the LTC pipes and 83 % of the total charge in the HTC pipes. Pipe length, its diameter and the relative positions of the condenser to the expansion valve would potentially reduce the mass of working fluid in the pipes. The reduction of working fluid mass in the compressor is dependent on the solubility of the fluid in the lubricant. Selection of suitable lubricant will be important to reduce the charge.

With a cumulative charge of 89.2 % (Theoretical analysis) and 75 % (Model test facility) of the total charge in the system, the liquid receivers and the heat exchangers on the high-pressure side of the system represent the important components for charge reduction. To evaluate the impact of these components to charge in a system, 5 different configurations of heat pumps are developed and shown in Fig 1. The propane and butane cycles are considered thermodynamically similar and are charged with an equal mass of fluid for both cycles for the analysis, similar to the test facility.

The 5 configurations are:

1. System with high-pressure receivers and suction accumulators (HPR_SA). This is the test facility configuration
2. System with high-pressure receivers and internal heat exchangers (HPR_IHX)
3. System with suction accumulators (SA)
4. System with internal heat exchangers and suction accumulators (IHX_SA)
5. System with internal heat exchangers (IHX)

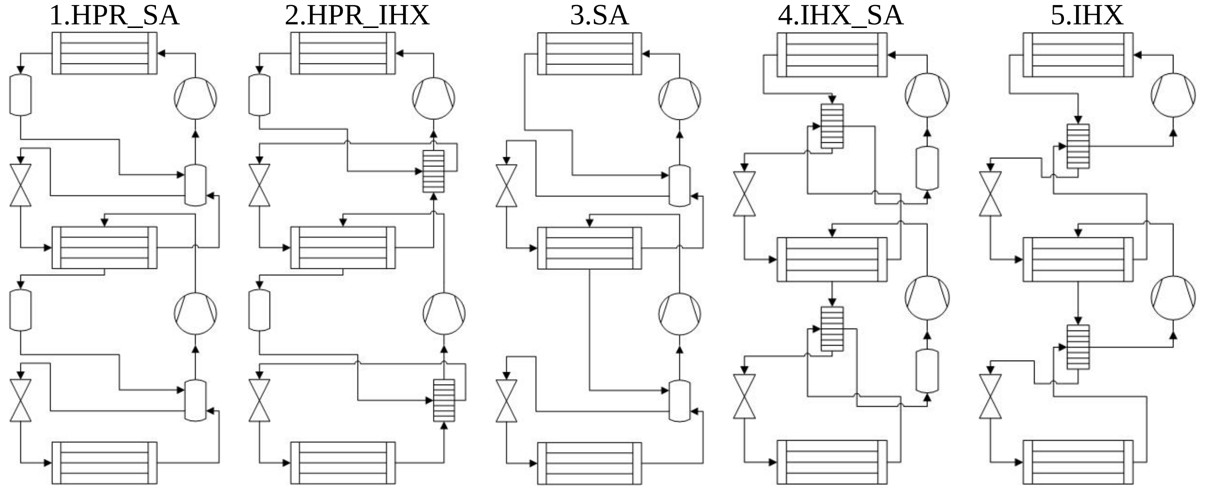

Figure 1: Schematic representation of the 5 configurations evaluated. 1.HPR_SA is the configuration of the test facility

3. RESULTS

3.1. The High Pressure Receiver (HPR) Sizing

The high-pressure receiver (HPR) serves the function of maintaining a separation of liquid and vapour from the condenser during variations in system operation, provide a charge buffer due to leakages and store working fluid during maintenance. The first function ensures the inlet to the expansion valve is in liquid state to minimize flash gas formation. During off-design conditions (variation in the flow rate, inlet or outlet temperature of the heat sink), the vapour-liquid ratio in the HPR varies. This amount of variation is partly dependent on the amount of working fluid charge in the system. To prevent dry-out of the HPR during off design conditions, there will be a minimum charge required for stable operation.

The sizing of the HPR is an important component design for minimizing working fluid charge. An HPR with more volume than required will result in dry-out for an optimal charge, and will appear to require more charge than necessary. If it is sized too small, it may not properly perform other functions in the heat pump effectively, like storage capacity for working fluid. Analysis is therefore performed for both the required size of the HPR and the amount of charge for stable operation.

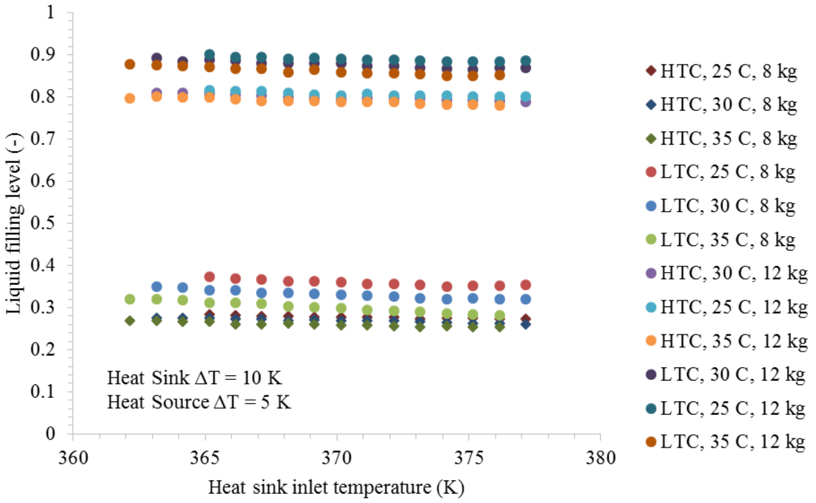

Figure *2*

Figure 2: Liquid filling level in the separators (0.02m^3) at varying operating conditions. The heat sink and heat source are varied by 10 K and 5 K respectively

Figure 2 shows the effects of varying the operating conditions of the heat pump with respect to charge of working fluid. At both 12 kg and 8 kg, the liquid fraction in the separators sized at 0.02 m^3 varied by less than 5 % even with conditions varying up to 10 K in the heat sink inlet temperature and 50 % deviation in heating capacity. At 30 % liquid volume for the 8 kg charged heat pump system, the performance of the heat pump is unaffected as the high density ratios of liquid to vapour compensates for the variations in operating conditions. The relatively small amount of changes in liquid fraction indicates the possibility to reduce the charge by lowering of the required liquid filling level of the HPR and consequently the size of the separator.

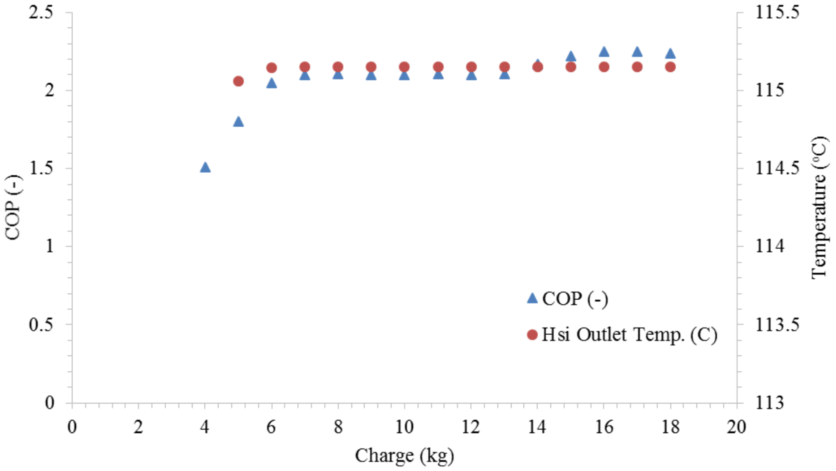

Figure 3: Performance of the heat pump and heat sink discharge temperature at different charge of working fluid

Figure 3 shows the performance of the heat pump as the charge of working fluid is reduced. The COP and heat sink discharge temperature are constant irrespective of charge between 7 and 13 kg. This region is the minimum and maximum liquid fraction in the HPR. The COP is higher with more charge above 13 kg. At this charge, the HPR is filled with liquid and sub-cooling begins in the condenser. At lower charge, the COP and heat sink outlet temperature reduces. There is incomplete condensation and the formation of flash gas.

While the HPR provide certain functions to the heat pump cycle, it adds to the volume that have to be filled with more charge. Though the liquid fraction can be minimized, having extra working fluid in liquid state increases the charge in the system. The HPR also prevents sub-cooling of the fluid in the condenser until the volume is completely filled with liquid. As seen in Figure 2, a charge greater than 13 kg will be required to have sub-cooling effect, which increased the COP of the heat pump.

3.2. Heat exchangers volume

The heat exchangers used in the 20 kW test facility are plate heat exchangers. As observed by (Ayub, 2003), the use of plate heat exchangers in refrigeration and heat pump system will lead to lower charge due to their compactness. An important feature of this compactness is the channel volume (space in-between plates), together with the number of plates, they determine the capacity of the heat exchanger and the mass of fluid in it. This channel volume affects the pressure drop, heat transfer coefficient and the mass flow rate possible through the heat exchanger.

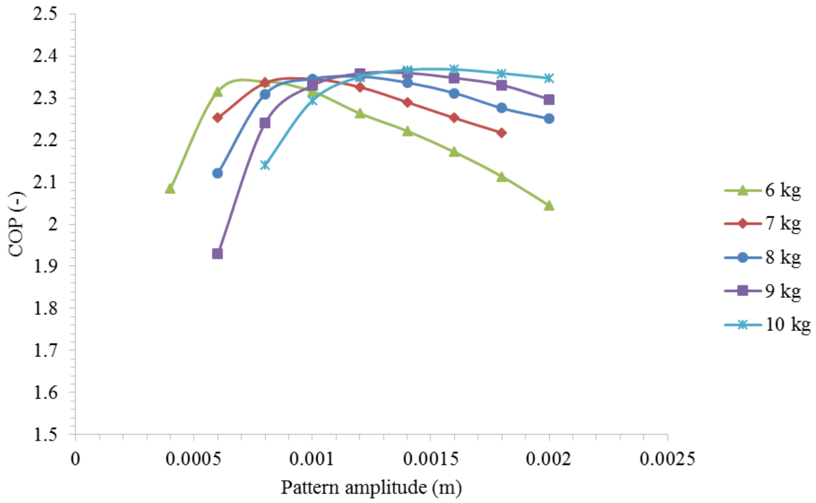

Figure 4: Performance of the heat pump with varying channel volume. Each plate area is constant with increase in plate separation

Fig. 4 shows the performance of the heat pump when the channel volume is increased. The volume is increased by varying the pattern amplitude of the plates and keeping the plate area constant. The result shows that there is an optimal channel volume for the highest COP for every working fluid charge. Deceasing or increasing the channel volume beyond this point will lead to a lower COP of the heat pump. For a higher COP, the channel volume of the plates will increase requiring more charge in the system. A trade-off is needed between the COP and the system charge.

3.3. Heat Pump Configurations

Reduction in the size of the HPR would potentially lead to a lower charge of working fluid. This is limited to the minimum amount possible if the HPR is not installed in the heat pump. Operating without an HPR will eliminate the functions associated with it, but there will be a reduction in charge required and an increase in COP due to sub-cooling in the condenser for equivalent charge of fluid. Figure 5 shows a comparison between different configurations of heat pumps for the reduction of charge and the influence on the COP.

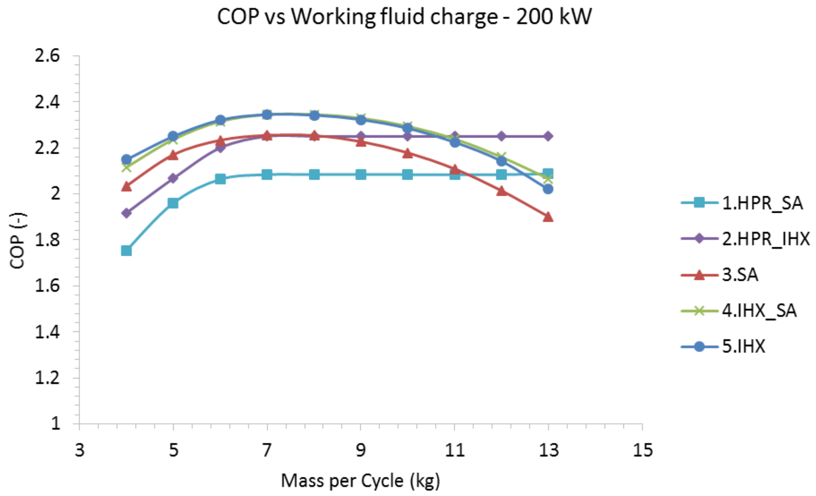

Figure 5: Performance comparison for different amount of charge in the heat pump

In Fig. 5, the 1.HPR_SA configuration represents the test facility. There is a constant COP between 7 kg and 13 kg equivalent to a minimum and maximum liquid fraction in the HPR. The 2.HPR_IHX configuration replaces the SA with a heat exchanger that sub-cools the fluid at condenser discharge and then superheats the fluid at compressor inlet. In this configuration, the sub-cooling is constant and within the IHX not the condenser with changes in charge. The COP is therefore also constant with varying charge as the HPR liquid fraction changes. The sub-cooling effect shows a COP improvement of 8 % for the same charge of 8 kg per cycle as the reference model. The 3.SA configuration is without the HPR and IHX components. The COP is improved by up to 8.1 % compared to the reference model as the charge is redistributed within the cycle. The extra charge in the condenser allows for some sub-cooling of the fluid leading to the improved performance. Without the HPR the COP changes for every increase in the charge. The cycle will therefore have an optimal charge for best COP.

The 4.IHX_SA and 5.IHX configurations are very similar in performance with changes in charge. The volume added by the SA (0.02 m^3) though equal to the HPR removed, is not significant as the fluid will be in vapour phase during normal operation. Without the HPR, the benefits of sub-cooling is maximized in both the condenser and the IHX. This results in a higher COP up to 12.6 % or a reduction of 50 % (4 kg) in charge for an equivalent COP to the reference model as seen in Fig. 5. The 4.IHX_SA configuration will be the preferred choice due to the added benefits of the SA without a substantial increase in charge despite volume increase. The SA in the 4.IHX_SA configuration can also be used as a working fluid storage during maintenance, which is one of the functions of the removed HPR.

4. CONCLUSION

This study evaluated the possibilities to reduce the charge in a cascade configuration high temperature heat pump for industrial applications. The heat pump is designed to use hydrocarbons propane and butane as its working fluid, due to their favourable thermodynamic properties for high temperature heating and no negative environmental effects. Hydrocarbons are flammable and the HTC fluid butane is relatively expensive. The reduction of the charge in the system will benefit both the safety requirements and the investment and operating cost of the heat pump.

The research utilized a 20 kW test facility to develop a theoretical model of 200 kW capacity to evaluate charge distribution within a heat pump system. The study showed that the separators and the heat exchangers at the high-pressure side of the two cycles had the most mass of fluid in the system. By changing the heat pump configuration, a reduction of 50 % in charge was achieved for an equivalent COP of the test facility configuration or an increase of 12.6 % in COP for an equivalent charge. The improvements came by the removal of the HPR and the sizing of an IHX. The heat exchangers charge reduction required a trade-off between the COP and the amount of charge using a plate heat exchanger. To reduce the charge in heat exchangers, a different type of heat exchanger with smaller channel volumes with higher heat transfer coefficient will be required.

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NOMENCLATURE

COP	Coefficient of Performance
HC	Hydrocarbons
HTC	High Temperature Cycle
HTHP	High Temperature Heat Pump
HPR	High-Pressure Receiver
IHX	Internal Heat Exchanger
LTC	Low Temperature Cycle
SA	Suction Accumulator

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