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Test Rig Hydrocarbon Mixtures For Multi-Source Commercial Heat Pumps

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Test rig for hydrocarbon mixtures for multi-source commercial heat pumps

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ABSTRACT

The transformation of heat supply in urban areas from fossil based to renewable is a key factor to reduce the CO2 emissions. Every existing district network has its own characteristics in heat supply temperature (>90°C), capacity, age, heat generation technology, and options to change the volume flow to keep the heat supply costs low. Decentralized non-used heat sources in urban areas can be implemented with multi-source heat pumps. These sources could be cold water networks, sewage up to server farms and low- and mid-temperature district heating networks. The challenge for multi-source heat pumps are the different temperature levels of each source. To investigate different multi-source scenarios for heat pump technology a fluid screening has been the foundation for a test rig design; different compressor configurations are also analyzed in order to consider the entire improvement potential integrally. Regarding the working fluids the focus will be hydrocarbon refrigerants and mixtures for heat pump heating capacity of 5 to 50 kW. The source temperatures are varied between -10 °C and 50 °C, the sink temperatures between 30 °C and 85 °C. The temperature spread between inlet and outlet of the heat source/heat sink is investigated between 5 and 25 K. The focus of the system is the compression technology: A scroll compressor and two reciprocating compressors are installed and can be tested separately or in a booster option with an intercooling. A comparison and interaction between refrigerant mixtures, compressor technology, source/sink temperature and temperature glide should be enabled.

1. INTRODUCTION

The transformation of heating grids encompasses two distinct perspectives: the development of newly designed district networks and the adaptation of existing systems. Newly designed networks can be engineered and constructed to accommodate lower supply temperatures, facilitate multi-source heat pumps, and integrate building infrastructure tailored to network specifications. Conversely, existing networks must undergo thorough evaluation to ascertain the feasibility of reducing supply temperatures. Such evaluations require a comprehensive analysis of heat generation costs, investment considerations, supply contracts, network infrastructure, heat generation methods, and potential modifications to customer-side supply systems, all of which pose significant challenges in their own right.
Transformation needs have been shown in the research of e.g. Lund et al (2014), Robbi (2013) and Xiao *et al.* (2023). Another example is a new build grid in Celle (Wördemann and Ortmann, 2021).

1. Heat pump/chiller
2. Low-temperature grid
3. Passive energy management (Thermal storage and multiple diverse supply technologies)
4. Overall energy system control

Figure 1: E.ON ectogrid tm(Website 06.03.2024)

In addition to these individual challenges, both new and existing networks must contend with the concept of temperature glide from the user side. The E.ON ectogrid™ exemplifies the evolving requirements of heat pumps within district heating systems (see Figure 1, E.ON ectogrid™). Future systems are envisioned to incorporate two stages of heat pumps: the initial stage integrated into the heating grid's supply, and the booster stage serving to boost supply temperatures within buildings. Moreover, every booster heat pump in the grid could be utilized to cool the grid system, providing cooling capacity to other users, thereby transforming the system into a versatile heating and cooling solution. Consequently, optimizing the refrigerant temperature glide of the working fluid of the booster heat pump on the source side emerges as a critical factor in enhancing system efficiency. Given that existing heat pumps typically do not utilize zeotropic mixtures, there exists a research imperative to focus on multi-source heat pumps optimized for temperature glide on the source side.
The ultimate goal of this research is to identify a heat pump configuration utilizing a refrigerant mixture that exhibits superior COP across the majority of the defined operating points, compared to heat pumps without temperature glide. The diverse approaches to the transformation of heating grids underscore the importance of delineating the boundaries of booster heat pumps (see Table 1). Boundaries of the user side, which set standard conditions for heating and domestic hot water provision in multifamily homes, serve as a foundational reference point. Of particular challenge in the context of multi-source systems is accommodating supply temperatures ranging from +50 °C down to -10 °C. Furthermore, the temperature differential between the evaporator inlet and outlet presents a considerable variation, spanning from 3 K to 30 K, further challenging he operational considerations for booster heat pumps within these evolving heating grid environments.

Table 1: Boundaries heating grids

District heating grid			**Local user**	
Source	Temperature	Temperature spread (inlet/outlet)	Temperature sink	Temperature spread (inlet/outlet)
Middle temperature district heating	25 – 50 °C	15 – 30 K	35 – 70 °C	5 – 20 K
Cold temperature district heating	0 – 25 °C	10 – 25 K	35 – 70 °C	5 – 20 K
Sewage	5 – 25 °C	3 – 10 K	35 – 70 °C	5 – 20 K
Ice storage	-10 – 25 °C	3 – 10 K	35 – 70 °C	5 – 20 K

The limitations imposed by the boundaries of heating grids result in a notable variation in operating points. Systems operating within these constraints must contend with significant temperature spreads between the heat source and the heat sink, characterized by asymmetric thermal profiles. For instance, when the evaporator exhibits a temperature spread of 15 K between its inlet and outlet, while the corresponding temperature spread at the heat sink is only 5 K. Such disparities pose substantial challenges, particularly regarding the management of high evaporation temperature and the resulting an increased suction gas temperature, which in turn presents a potential challenge for effectively cooling the compressor motor. In addition, the high temperatures at the evaporator outlet raise concerns regarding system efficiency and longevity. Excessive heat can lead to increased wear and tear on system components, potentially reducing their operational lifespan and necessitating more frequent maintenance. Furthermore, the increased suction gas temperature may compromise the overall performance of the heat pump system, affecting its overall efficiency
The focus on natural refrigerants, particularly hydrocarbons, is crucial due to the environmental drawbacks and regulations associated with synthetic refrigerants. Synthetic refrigerants have a limited lifespan and/ or contribute to ozone depletion and/ or global warming. Prioritizing natural refrigerants aims to identify sustainable alternatives with effective cooling and heating capabilities and minimal environmental impact. This strategic shift aligns with efforts to mitigate climate change and promote eco-friendly practices in the heating and cooling industry.
In addition to the advantages of natural refrigerants, it is essential to consider the temperature glide phenomenon inherent in hydrocarbon mixtures. Temperature glide refers to the gradual change in temperature experienced by a refrigerant mixture during the phase change process. This characteristic becomes particularly relevant in scenarios with significant temperature spreads, as mentioned earlier. Harnessing the temperature glide of hydrocarbon mixtures intelligently can enhance the efficiency and effectiveness of heat pump systems, especially within the context of diverse operating conditions present in heating grids. Given these considerations, a pertinent question arises: Is it feasible to design a heat pump system capable of effectively utilizing the temperature glide of hydrocarbon mixtures

across all operating points. In this study, a comparison of different blends has firstly drawn with a fluid screening and the potential blends for the application have been derived. Based on these results a test rig is designed for future experimental investigations. The cycle design and component selection are subsequently discussed.

2. FLUID SCREENING

The evaluation of refrigerant blends featuring temperature glide characteristics has been made through the seminal research conducted by Zühlsdorf *et al.* (2018b). Given the inherent complexity of the operational scenarios, a four-component cycle has been employed for conducting the analyses. The natural blend compositions are systematically varied from 100% to 0% in increments of 10%, while ensuring a minimum vapor pressure of 0.8 bar. The configuration of the heat pump cycle encompasses a set of defined parameters outlined in the following table.

Table 2: Boundaries analyses

Refrigerant class	Blends	Compressor is. efficiency	Pinch point heat exchanger	Superheating	De-superheating
Natural refrigerants	Binary	65%	>5 K	>5 K	>5K

The foundation for the fluid screening process lies within table 2, which comprehensively delineates all specified boundaries encompassing the scope of sources and sinks. Evaluations of the variation of water temperature spreads have been shown e.g. by Brendel *et al*. 2024. From this extensive array of operating points, a test matrix for fluid screening was developed. The primary challenge lies in the evaluation of blend compositions, wherein nearly every test point necessitates distinct ideal compositions. Consequently, two distinct analyses have been undertaken: one focusing on identifying the top 10 refrigerant blend compositions (e.g. Propylene/Butane, [40 %, 60%] mole fraction), and another centered on determining the best average Coefficient of Performance (COP_H) derived from binary blend components overall, based on the arithmetic mean of mole fraction ranging from 10 – 90 %. Figure 2 shows the results of a few refrigerant compositions for the test point at sink 40°C up to 55°C and source 25°C down to 5°C as an example.

Figure 2: Results operating point sink (55°C/40°C) and source (25°C/5°C)

At this operation point, the binary blend components Hexane & Isobutane exhibited the highest average COP, considering the composition range from 10% to 90%. However, this blend is not included in the results because the evaporation pressure under this boundary condition falls below the minimum requirement of 0.8 bar. Consequently, the blends with the best average COP, are Propylene & Butane, Propane & Butane, and Isobutane & Isopentane in this case.

Given the variance each COP of every test points of the investigated binary mixtures, the average COP was chosen as the principal decision-making criterion. For example for the test point shown in Figure 2, the average COP calculated over the entire composition range of Propylene & Butane (10% to 90%) is 3.65% lower than the best blend composition of Propylene & Butane [60%, 40%]. Using this procedure, the top three average binary blend components

will be included in the result table of the following matrix (Table 3). This matrix is based on the operating points of the heating grids, providing an evaluation of the best binary blend components and the best refrigerant compositions for each operating point. However, because of the large amount of data points, it is not able to show all the interim results. Instead, the table shows the concept of the evaluation.
An ancillary outcome arising from the test matrix setup is the evaluation of results along the horizontal and vertical axes. Horizontally, the blends are evaluated at the given specific temperature requirements at the source and sink, with different temperature spreads of the heat source/heat sink (similar to the research from Zühlsdorf *et al.,* 2018b). Conversely, the evaluation of the vertical axis involves identifying the optimal blends across diverse source and sink temperatures at the same temperature spreads. Ultimately, the culmination of this analytical process yields the identification of the most favorable blend components situated within the lower right corner of the matrix.

Table 3: Test matrix operation points/refrigerants

		Temperature spread heat exchanger							**Best blend components**
Source		10 K	15 K	20 K	10 K	20 K	15 K	15 K	
Sink		10 K	15 K	20 K	15 K	15 K	10 K	20 K	
Temp. out condenser	Temp. in evaporator								
75°C	40°C								
75°C	25°C								
75°C	10°C								
55°C	25°C					Figure 2			
55°C	10°C								
Best blend components									**Overall best blend components**

The exploration of the top three average binary blend components has been conducted across each of the 35 distinct operating points. With the evaluation of the test matrix, Propylene & Butane appear the most in the top three, making them the most promising blend components. Table 4 displays the results derived from this analysis, highlighting the preeminent blend components. Based on these findings, the initial blends selected for testing in the new test rig comprise Propylene & Butane, alongside Propane & Butane.

Table 4: Favorite blend components with composition focus

Binary blend components	**Frequency in the Top 3**	**Composition focus (mole fraction)**
Propylene & Butane	39x	40/60 – 60/40 %
Propane & Butane	36x	50/50 – 60/40 %
Iso-Butane & Iso-Pentane	28x	50/50 – 70/30 %

Based on the results derived from the fluid screening process and the selection of the initial two blend components, it becomes imperative to streamline the test range of blend compositions to expedite the testing procedures. Therefore, the top 10 specific compositions out of all 35 operating points have been analyzed to define the composition focus for the binary blend components. The best compositions were rated according to their frequency in the top 10 compositions. This strategic approach aims to optimize testing efficiency and resource allocation, thereby facilitating a more targeted and expedited assessment of the blend compositions.

3. SYSTEM DESIGN

3.1. Experimental heat pump setup

In order to effectively address the complex requirements outlined in the introduction – including varying temperature levels, temperature gradients, booster options, and the use of refrigerant blends – a systematic approach was taken to design a comprehensive system capable of analyzing all pertinent factors. The resulting system design comprises a 5-

component cycle, consisting of a compressor, condenser, expansion valve, evaporator, and an internal heat exchanger (IHX). The research setups of e.g. Venzik (2019) and Arpagaus *et al.* (2018) have served as a valuable reference point. Of particular significance is the compressor aspect of the system, as Roskosch *et al.* (2021) and Brendel *et al.* (2023) have shown. Figure 3 shows the planned set-up of the experimental test rig at the TU Dresden where a scroll compressor and two piston compressors are integrated. The chosen scroll compressor has an expansive compressor map capable of accommodating suction gas temperatures of up to 30 °C. Besides, two piston compressors, derived from the product line from the same manufacturer, exhibit differing sizes and technical designs. This contrast allows for a comparative analysis of their performance when operating with the same refrigerant mixture. Notably, the piston compressors are engineered to withstand suction temperatures exceeding 50 °C, underscoring their suitability for handling high-temperature conditions within the system.

Figure 3: System architecture

The interconnection of the compressors offers notable advantages in terms of system flexibility and performance variation. Specifically, the scroll compressor and the two piston compressors can be operated separately – thus they can be effectively compared with each other in terms of their performance under single-stage compression conditions. Additionally, either the scroll compressor or the larger piston compressor can be operated together with the smaller piston compressor in a booster arrangement. This interconnected configuration not only enables comparative analyses between different compressor types operating under similar conditions but also facilitates the enhancement of overall system performance through a strategic compressor utilization.
A notable challenge in the system design is the oil management. To address this, all three compressors will be equipped with electric oil level regulators. The high variation in pressure levels and the use of booster configurations demand an effective oil management strategy. This requires the implementation of a sophisticated regulation system capable of simultaneously monitoring and controlling the oil levels across various test scenarios. Ensuring proper oil management is crucial to protect the system components from potential issues, such as compressor dry running, thereby ensuring their longevity and reliability.
The selection of compressors, combined with the variability of operating points, presented a significant challenge in the design of the heat exchangers. Given the diverse range of refrigerants, mixtures, compressor speeds, and temperatures involved, ensuring optimal heat exchange capacity proved to be complex. The capacity requirements varied significantly, ranging from below 5 kW to well over 50 kW, with a complete temperature spread of 5 – 25 K, highlighting the diverse demands placed on the heat exchangers. While capacities below 5 kW and above 50 kW are feasible, they may not fall within the range of the complete temperature spread due to volume constraints in both the heat source and heat sink. To address this challenge effectively, specific boundaries were established, focusing on two key refrigerants: butane and propane. For the design targeting the lower end of the capacity spectrum (5 kW), butane was selected as the primary refrigerant of interest. Conversely, for designs aiming at 50 kW, propane was identified as the focal refrigerant.
In addition, the secondary side of the condenser has been designed to accommodate water with a temperature spread ranging from 5 to 25 K. Similarly, the evaporator has been engineered to operate within the same temperature spread. However, on the secondary side of the evaporator, a water-glycol mixture consisting of 30 % glycol has been incorporated to avoid frost defects.

The design of the refrigerant receiver has been intentionally oversized, providing flexibility in the test rig's configuration regarding the mass of the refrigerant, thereby enabling the incorporation of various mixtures by simply adding refrigerant into the active cycle.

Figure 4: 3-D model of the planed heat pump setup

To validate the mass flow and mixture composition accurately, a Coriolis sensor has been integrated into the system. Positioned strategically between the refrigerant receiver and the expansion valve.
This positioning is particularly advantageous as it allows for continuous monitoring and adjustment of the refrigerant mixture, ensuring consistency and reliability in the experimental setup. Even in scenarios where there might be a shift in the mixture composition within the receiver, the density measurement conducted downstream, (see also Brendel *et al.* 2023), serves to corroborate and maintain the accuracy of the circulating mixture.
To regulate the internal heat exchanger (IHX), a three-way valve has been integrated into the system. This valve enables control over the mass flow, and consequently, the capacity of the IHX can be adjusted. However, due to the variation in mass flow rates associated with different refrigerants and mixtures across various operating points, there is a potential for the valve to encounter difficulties in regulating at the lowest set points of the valve. In anticipation of these challenges, the controller can be configured to transition from automatic mode to a constant signal mode when operating at or near the lowest set points. By maintaining a constant signal, the valve can effectively mitigate issues related to control challenges, ensuring stability and consistency in IHX operation.

3.2. Experimental hydraulic setup

To adjust the external boundaries, encompassing operating points in volume flow and temperature for inlet and outlet conditions, a hydraulic module has been designed as a separate module.
The modular design offers an innovative solution for optimizing the system's footprint. Its inherent flexibility allows for dynamic adjustments in configuration, enabling it to be compacted into a block-like structure or elongated to fit available space. This adaptability ensures seamless integration into diverse laboratory environments.
For an accurate measurement of the volume flow rates, magnetic inductive sensors have been installed at both the heat sink and the desuperheating sections of the system. Given that some operating points on the source side may be below 0 °C, necessitating the use of a water-glycol mixture, a Coriolis sensor was deemed the most suitable choice.
To accommodate the varied capacity requirements, dry-running circulation pumps have been employed, necessitating the use of various valves for the temperature control, inlet/outlet conditions, and volume flow. In both the heat source and heat sink sections, two 3-way valves and two 2-way valves have been installed for precise temperature control and throttling of volume flow rates.

Figure 5: 3-D hydraulic module (PEWO Energietechnik GmbH)

Figure 6: Hydraulic system schematic

The heating of the source is facilitated by the heat of the sink side, with provisions in place for an electric heater to supplement the heating capacity if necessary. Heat source temperatures can range from -10 °C to 50 °C. If the heat sink fails to reach the required inlet temperature, the surplus heat is dissipated the main chiller of the laboratory to prevent overheating. The desuperheating setup is simplified, featuring only one 2-way throttle valve and a dedicated wet-running circulation pump to regulate the specified boundaries effectively. An overview of all boundary conditions is shown in the following table.

Table 5: Boundaries hydraulic module

	Medium	Temperature inlet	Temperature spread (in/out)	Capacity
Heat source	Water/Glycol 30 %	-10 – 50 °C	5 – 25 K	5 – 50 kW
Heat sink	Water	25 – 80 °C	5 – 25 K	5 – 50 kW
Desuperheating	Water	15 – 80 °C	3 – 15 K	0.5 – 10 kW

3.3. Main components test rig

The following table 6 shows the main implemented components of the test rig. All components have been chosen for the use of hydrocarbons.

Table 6: Components of heat pump and hydraulic system

Component	*Modell*	*Manufacturer*	*Details*
	Heat pump architecture		
Scroll compressor	GSP60137ZL	Bitzer	22,20 m^3/h at 50Hz, BSG68K
Piston compressor	4DESP-7P	Bitzer	26,84 m^3/h at 50Hz, SHC226E
Piston compressor	4VESP-10P	Bitzer	34,73 m^3/h at 50Hz, SHC226E
Condenser	B85Hx40/1P	SWEP	Heat transfer area 2,28 m^2
Evaporator	F80Hx40/1P	SWEP	Heat transfer area 2,28 m^2
Desuperheater	B12Lx30/1P	SWEP	Heat transfer area 0,784 m^2
IHX	B12Lx30/1P	SWEP	Heat transfer area 0,784 m^2
Check valve	EVR20	Danfos	K_{vs}=6 m^3/h, (max. 45 bar, 105 °C)
Oil separator/collector	TURBOIL-R-P14 309 S	Carly	V_{total}= 7,6 L, $V_{oil\ collector}$=3 L
Oil level valve	ERM6	ESK-Schultze	V = 0,05 L, (max. 60 bar, 85 °C)
Check valve	EVR3	Danfos	K_v= 0,26 m^3/h, (max. 45 bar, 105 °C)
Reciver	FS76(P)	Bitzer	V = 7,8 L, (max. 33 bar, 120 °C)
3-way valve	M3FK15LX	Siemens	K_{vs} = 3 m^3/h, (max. 32 bar, 120 °C)
Expansion valve	MVL661.15-1.0	Siemens	K_{vs} = 1 m^3/h, (max. 45 bar, 120 °C)
Temperature sensor	PT1000	TMH	Class A, three wire circuit
Pressure sensor	PAA-23SY	Keller	0-40 bar abs, 4-20 mA, FS 0.25
Coriolis-Sensor	OPTIMASS 6400 C	KROHNE	max. 40 bar, 150 °C, +/- 0,05 %
Controller		WAGO	

5. CONCLUSIONS

The diverse operating conditions of heating grids on both the heat source and heat sink sides have shaped the foundation of the test matrix. Propylene/Butane and Propane/Butane emerge as the optimal natural blend components for these conditions. The main mole fractions of interest range from 40/60 % to 60/40 %.
The newly developed test rig, featuring a versatile hydraulic module, provides a platform for conducting intricate research on hydrocarbon refrigerants. This setup allows the comparison of different compressor types operating with identical refrigerant combinations and across various operating points. A particular emphasis is placed on exploring the advantageous characteristics of hydrocarbon mixtures, especially concerning their compatibility with scroll or piston compressors and the behavior with blends.
Furthermore, the test rig enables the investigation of the behavior of different compressors when configured as a booster setup. By examining how different compressors perform in this capacity range with different refrigerants and mixtures, valuable insights can be gleaned regarding their efficiency and effectiveness in enhancing performance of components and system
Concurrently, a Dymola model of the heat pump system will be developed and valided using the experimental data. This model will serve as a complementary tool, enabling parameter studies to explore additional operating points. By leveraging this modeling approach, the extensive array of variables inherent in the system can be simulated and verified alongside the experimental data obtained from the test rig. This combination of testing and modeling facilitates a synergistic approach, allowing for the acquisition of valuable insights and knowledge in a shorter timeframe. The ultimate goal of this research endeavor is to identify a heat pump configuration utilizing a refrigerant mixture that exhibits superior COP across the majority of the defined operating points, compared to heat pumps without temperature glide.

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