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R744 HEAT PUMPS WITH EJECTORS: PROJECTS, OBJECTIVES AND RESULTS

Oliver Javerschek*, Alessandro Silva, Miguel Boscan ****
*BITZER Kuehlmaschinenbau GmbH, Peter-Schaufler-Strasse 3,
72108 Rottenburg-Ergenzingen, Germany
+49 (0)7031 932-244, oliver.javerschek@bitzer.de
**BITZER U.S. INC., 4080 Enterprise Way,
GA 30542 Flowery Branch; United States of America
+1 (770) 718-2900, asilva@bitzerus.com
+1 (770) 718-2900, mboscan@bitzeruse.com

ABSTRACT

How should heat pumps with ejectors be seen in the context of discussions about reducing global CO_2 emissions, the energy transition, energy supply and grid stability? It is obvious that space heating and water heating are responsible for a large proportion of global CO_2 emissions. A gradual conversion of the energy supply to renewable energies will ensure that the proportion of CO_2 emissions from heat pumps will continue to fall in the future. Heat pumps are therefore a crucial building block for a sustainable heat supply. This paper deals with current BITZER projects in the field of R744 heat pumps with ejectors in the output range from 40 kW to several megawatts. Projects, objectives and some results are presented.

Keywords: heat pumps – ejectors – carbon dioxide

1. INTRODUCTION

On June 24, 2021, the EU Parliament adopted the EU Climate Law. Europe's targets are enshrined in the "Fit for 55" climate package and include a 55 % reduction in greenhouse gas emissions by 2030 and a further target of becoming climate neutral by 2050. With regard to energy supply, Parliament approved a new target in September 2023. The aim is for 42.5 % of energy to come from renewable sources by 2030. However, the EU member states were asked to aim for a 45% share of electricity generation in industry, buildings and transport sectors. This ambitious target is also supported by the Commission as part of its REPowerEU plan. Current EU statistics show that the share of renewable energies in 2023 was 40.5 percent. The share of onshore and offshore wind energy plants was an impressive 18.9 % (1). In the EU, the energy demand for heating and cooling is around 50 % (2) . The majority of heating and cooling energy requirement is still generated from fossil fuels. In addition, only a very small proportion of the waste heat generated in the EU is currently used. In its 2020 report on heating, the IEA stated that the decarbonization of the sector is not progressing fast enough (3). An updated report by Eurostat puts the current share of renewable energies in the discussed sector at 24.8 % (4). In order to achieve the EU's climate and energy targets mentioned at the beginning, it is therefore necessary for the heating and cooling sector to become more efficient and carbon-neutral. This can be achieved through 100 % renewable energy sources and the use of waste heat. District heating and cooling (DHC) is a proven solution for the provision of heating, hot tap water and cooling. The systems are predestined for feeding in locally available, renewable and low-carbon energy sources. For example, solar thermal energy, geothermal energy and waste heat. This also means that the energy supply becomes more independent, as it is not reliant on just one energy source. Advanced district heating networks are adapted and optimized to local conditions. Another positive aspect is that large, centralized systems can often be operated much more efficiently than several smaller systems. Research and development and the resulting innovations continue to drive progress. In Europe, this is clearly demonstrated by the many research projects, for example in Denmark, and innovative start-ups that are developing new applications.

In North America, the affirmative stance of the U.S. government on international climate change agreements, as seen in the Paris Climate Accord (5) and the Kigali Amendment to the Montreal Protocol (6), underscores its dedication to fostering a global clean energy economy. These agreements have set ambitious targets for the United States, aiming to reduce greenhouse gas (GHG) emissions by 50%–52% from 2005 levels by 2030, decarbonize the U.S. power sector by 2035, and achieve a net-zero emissions economy by 2050 (7). Federal efforts have placed significant emphasis on mitigating emissions from buildings, leading to substantial investments in modernizing and enhancing buildings for affordability, resilience, accessibility, energy efficiency, and electrification (8). Moreover, a suite of policies and targeted actions has been put in place to support research into heat pump technology, expand its deployment, and address vulnerabilities within the supply chain. The government's decarbonization agenda, along with supportive policies and programs, presents an unprecedented opportunity for advancing the research, development, and deployment of heat pump technologies, which are deemed indispensable for realizing these objectives. However, a comprehensive review of the heat pump market has revealed several areas and sectors requiring tailored solutions to incentivize the adoption of heat pump technology. These solutions encompass increasing supply chain capacity, expanding the workforce through training and education initiatives, enhancing the affordability and accessibility of heat pump technology, and bolstering the supporting grid infrastructure. Key technological challenges include the absence of regional solutions tailored for colder climates, high upfront costs, and intricate design and control of components and systems for hybrid heat pumps with multiple heat sources. There could also be compromised energy benefits due to installation challenges, and spatial constraints limiting heat pump installations. Addressing these challenges necessitates targeted research efforts, including improving the efficiency and capacity of heat pumps for various climate conditions. Reducing the installation cost, enhancing the reliability of high-efficiency systems, devising solutions for challenging installations, and developing alternative refrigeration technologies and lower-GWP refrigerants to minimize direct emissions are the goals. This requires a multidisciplinary approach encompassing economic, social, political, and technological innovations from all stakeholders, including the development of efficient systems with optimized components, intelligent monitoring, optimal control mechanisms, innovative system integration, aggregation strategies, and effective servicing protocols (9). Canada has also committed to achieving net-zero emissions by 2050 (10), joining over 120 countries, including all other G7 nations. The Canadian Climate Institute identifies heat pumps as an effective tool for reducing emissions from buildings and homes, as they generate heat and cooling from electricity instead of burning fossil fuels. In October 2023, the Government of Canada announced enhancements to the "Oil to Heat Pump Affordability Program (OHPA)" to make the switch from heating oil to electric heat pumps more affordable for low-to-median-income households (11). In terms of district heating and cooling (DHC) development, neither carbon trading, carbon taxes, nor investment subsidies are common in supporting such development in North America; however, states and provinces do use some of these incentives. There are significant barriers to DHC development in North America, including national policies that do not support this kind of technology, and financially and politically weak municipalities have limited options for supporting it. Furthermore, high investment costs and long payback times deter private sector investors from DHC, and residential customers are more difficult to attract than public and commercial customers (12).

2. DISTRICT HEATING AND COOLING (DHC)

2.1 FORCO2 project

The Danish Technology Institute, DTI, leads the FORCO2 project, which is supported by the Danish research program EUDP (Energy Technology Development and Demonstration Program). The Danish program supports private companies and universities in the development and demonstration of new energy technologies. The project is managed by Jóhannes Kristófersson. Participating companies are Fenagy, Danfoss, Kelvion, Güntner, EICon, CO2X and BITZER. The main objective of this project is the development of a newly designed, industrially manufactured, reversible chiller and heat pump unit based on the natural and safe refrigerant R744, with the target market being air conditioning systems and industrial processes. In the summer months, the system is used as a chiller with heat recovery to produce domestic hot water for air conditioning systems or to cover the low-temperature loads for industrial processes with heat recovery for hot water production. In winter, on the other hand, the system operates as a heat pump to cover the demand for thermal energy. The proposed system is shown in Figure 1. If the new system is compared with the state of the art in the form of a chiller and an electric boiler, it is possible to achieve significant energy savings.

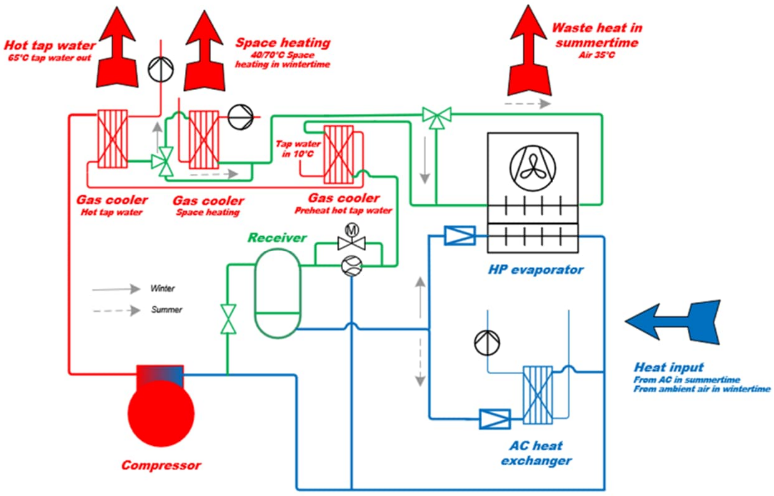


Figure 1: Simplified sketch of the newly developed system, courtesy of the DTI

A general comparison between the current state of the art system and the new system solution is shown in Figure 2. A conventional chiller with an air-cooled condenser and an electric boiler are compared with the system developed as part of the project. Heating and cooling requirements are assumed to be 2 MW and 1 MW respectively. The coefficient of performance (COP) with the current state of the art solution is only 1.33. In contrast, the new approach enables an increase in efficiency of 451 %, which corresponds to a COP of 6.0. Even if heating and cooling requirements are set at 1 MW and 1 MW respectively, the comparison still shows an increase in energy efficiency of 327 % with calculated COPs of 5.30 vs. 1.62. This shows a significant gain in energy efficiency. By combining increased energy efficiency, reuse of waste heat and electrification, this research program breaks new ground and addresses the challenge of the future by enabling clean and energy-efficient heating and cooling for industrial processes and large buildings. All this by combining a chiller (water chiller) and a heating system (heat pump) in a single unit.

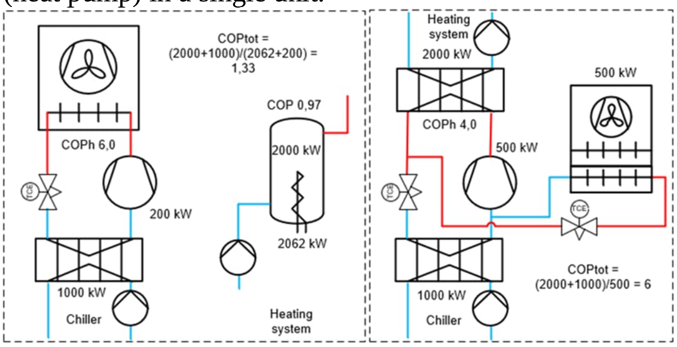


Figure 1: Comparison of Energy efficiency of state-of-the-art (left) and the reversible unit (right), courtesy of the DTI

The system being researched and worked on as part of the FORCO2 project is located in the laboratory at the DTI in Arhus. It is a low-lift system with ejectors with partially flooded evaporators. Active oil management with a low-pressure oil reservoir is considered. Four BITZER compressors of type 8FTE-140Z with on board OLM-3 oil level regulators, developed and optimized for this application, are applied. At the nominal design point, the compressors deliver a mass flow of more than 28,000 kg/h with a power input of around 400 kW. From the perspective of a compressor manufacturer, most of the measurements and tests in the DTI laboratory focus on application-specific findings. For example, the coordination of oil management. Figure 3 shows a data log of the IQ-Module of a compressor in operation. The recording shows an example of the operation in low-lift ejector mode. At 45 bara suction, 110 bara discharge pressure and 10 K superheat, the compressor represented in the data log displaces a mass flow of 6,227 kg/h with a power consumption of 103 kW at 50 Hz operation. The lower portion of Figure 3 shows the injection cycles of the OLM-3 oil level regulator. In this test, the oil level in the crankcase was regulated between 70 and 40 %. In addition to the variation of different regulated oil levels in the crankcase, the required injection cycles with varying-differential pressures are also examined in order to define an optimum oil management for the efficient operation of the system. For example, detailed performance maps can be generated for the oil management system. These then show the necessary injection cycles of the oil level regulator depending on the regulated oil level in the compressor crankcase and the prevailing differential pressure for the oil supply, based on constant compressor mass flows and oil carry over rates (OCR). For a compressor mass flow of around 8,000 kg/h, for example, the differential pressure of <2 bar is no longer sufficient to keep the compressor in operation without an oil alarm. The OCR that were measured as part of the project also confirm that the very low values are not only measured in the laboratory, but are also present in a stable running system under real conditions and under the influence of all regulation and control elements. The measured relative OCR for mass flows up to 10,300 kg/h indicates very low values, which are always below 0.5 %.

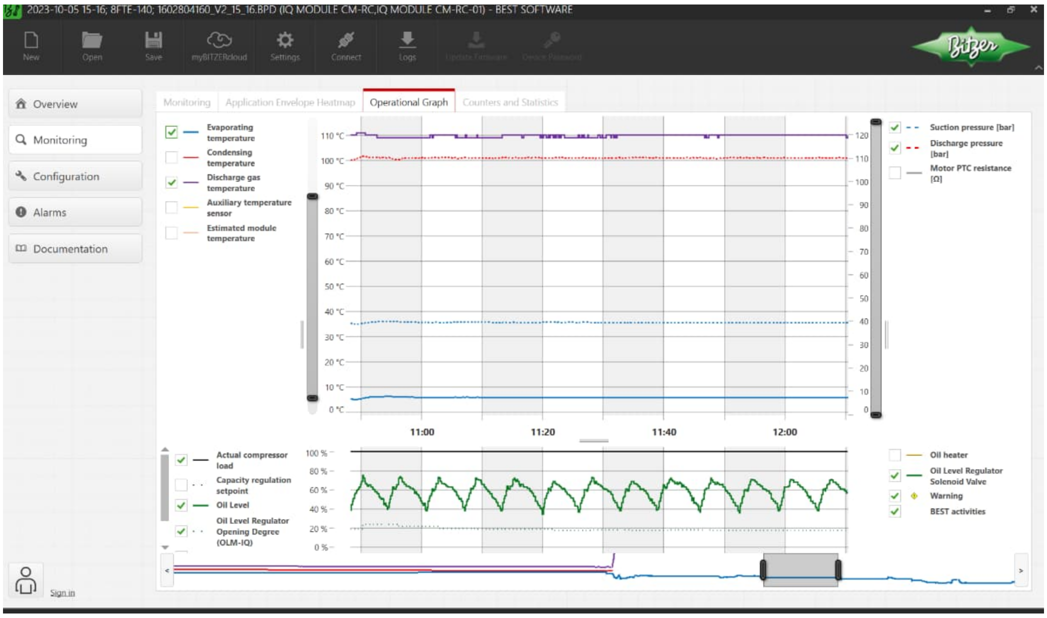
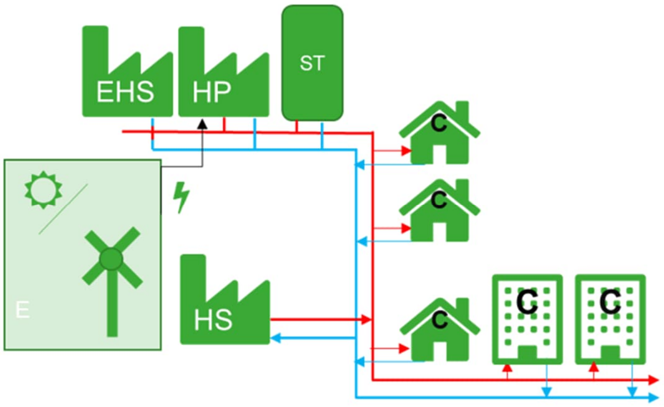


Figure 3: Operational live log of a compressor in operation

2.2 Installations in operation

Similar to the widespread adoption of R744 in refrigeration technology during the 2000s, another development is currently unfolding in Denmark, serving as a positive example for many European countries. The share of district heating in Denmark's heat supply is remarkably high. Already 66 % of all Danish housholds are connected to district heating networks. This equals a total number of 1,843,774 housholds and 3.7 Million people. The energy demand for district heating networks in Denmark is fulfilled by 76 % on renewable energy sources (13). Denmark's district heating networks are considered highly efficient. State-of-the-art technologies, including heat pumps using natural refrigerants, are applied. Additionally, intelligent network infrastructure ensures efficient distribution and utilization of thermal energy. Furthermore, thermal energy storage provides opportunities to create flexible networks and advance the integration of renewable energy sources. Because the use of wind and solar energy can lead to fluctuations in electricity generation, which can impact network stability in the form of voltage variations and frequency deviations, ensuring network stability is a crucial factor in integrating renewable energies. The rapid and flexible availability of a heat pump, which allows for the storage of wind or solar energy in the form of thermal energy, helps to ensure network stability. Additionally, thermal energy storage can help balance peak loads in district heating networks by storing heat energy for covering peak demand. Thus, the development in Denmark demonstrates that district heating networks play a significant role in transitioning to a sustainable and low-carbon energy supply, especially when combined with renewable energies and efficient energy storage technologies, as displayed in Figure 4.



Item	Explanation
EHS	Existing Heating System
HP	Heat Pump
ST	Storage Tank
HS	Heat Source/Waste Heat
C	Heat Consumer
E	Electrical energy sources

Figure 4: Simplified sketch of a district heating system, reference:

The company Fenagy is at the forefront of integrating R744 heat pumps in the megawatt power range within district heating networks in Denmark. These systems primarily consist of Air-To-Water (A2W) heat pumps with a High-Lift ejector application. In this configuration, the applied ejectors facilitate the transfer of mass flow from the first compressor stage to the parallel compression stage, emphasizing the positive effects of parallel compression. The efficiency improvement is more pronounced when the heat sink temperature on the gas cooler side is higher. Interestingly, the High-Lift application proves to be less sensitive than the Low-Lift application when dealing with a wide range of heat sink temperatures on both the gas cooler and evaporator sides. When the potential energy on the motive side of the ejectors is insufficient, the systems can adjust the load by either shifting it to the first compressor stage or operating in flash gas bypass mode. In terms of motor efficiency, the industry adheres to the IEC Standard 60034-30 for the use of open compressors. However, BITZER does not manufacture open compressors for R744 applications. Therefore the newly developed semi-hermetic 8-cylinder compressors are manufactured with a suction-gas-cooled high-efficiency motors, specifically developed for this type of compressor. The deployed asynchronous motors exhibit an efficiency well above 90% at both minimal and maximum torque requirements, making them comparable to motors referenced in the previously cited standard. A comparison of motor efficiency based on a standardized torque was presented by BITZER at the IIR Conference in Ohrid, organized by Prof. Risto Ciconkov, back in 2021. In Fenagy's systems, the predominant compressor types have been the 8CTE-140Z and the 8FTE-140Z, with theoretical displacement volumes at 50 Hz of 99.2 m^3/h and 69.4 m^3/h, respectively. Additionally, the 8DTE-140K type with a displacement volume of 82 m^3/h will be employed in the future. For the A2W heat pump commissioned in Vildbjerg in October 2023, a total of twelve 8CTE-140Z compressors and six 6DTEU-50LZ compressors are utilized across three systems. Operating at an ambient temperature of 5°C and water temperatures of 38°C and 68°C, the system provides a nominal heating capacity of 6 MW while achieving a COP of 3.2. To achieve this nominal performance, a total evaporator surface area of 540 m^2 is necessary, distributed among 18 evaporators, each equipped with 10 fans. The refrigerant charge amounts to less than 0.5 kg per kW of capacity, highlighting the system's compact and optimized design. Notably, the warm water storage tank boasts a capacity of 3,000 m^3. Images 1 to 3 provide impressions of the installation in Vildbjerg.

Pictures 1 to 3: Images taken from the installation in Vildbjerg

In December 2023, an installation in Farevejle was put into operation. It comprises of a combination of a 4 MW air-to-water (A2W) heat pump and a 1.5 MW water-to-water (W2W) heat pump**,** utilizing a total of 18 compressors. Remarkably, the hot water storage tank has a capacity of 4,000 m³**.** The first heat pump with BITZER 8-cylinder compressors commissioned by Fenagy, employs eight machines of the type 8CTE-140Z and boasts a nominal heating capacity of 4 MW. This system has been operational since March 2023.

3. EJECTOR PERFORMANCE MEASUREMENTS

In 2022, work by the company BITZER presented the development of a calculation model for ejectors. The model is based on three sub-modules: the geometric model, the motive mass flow model and the pressure stroke model. The motive mass flow model and the pressure stroke model are semi-empirical and depend on reliable measurement data. An ever broader base of measurement data will ultimately be used to re-correlate the models in order to calculate even more accurate performance data. It turned out to be a challenge that not many laboratories or companies have the possibility to measure ejectors performance with large nominal capacities under laboratory conditions. The ejector type HDV-E65 discussed in this paper was measured in a laboratory of an OEM. The Figure 5 provides an impression about the operated test conditions in a p,h-diagram. The measuring points with motive pressures between 80 and 100 bara are examined in the following. For constant motive pressures, the motive temperature varied with different opening degrees of the ejector. The suction pressure of the ejector was kept constant at 29 bara with an average superheat of 14 K. Pressure lift and entrainment were determined as a function of the described input conditions. The green dotted line shows the typical control function of a WURM controller for the optimum discharge pressure and is given as an example.

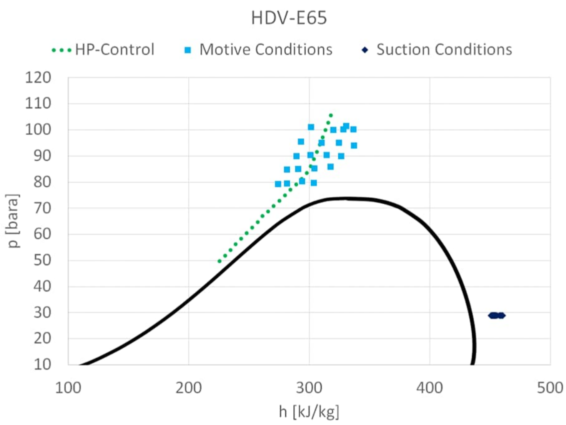
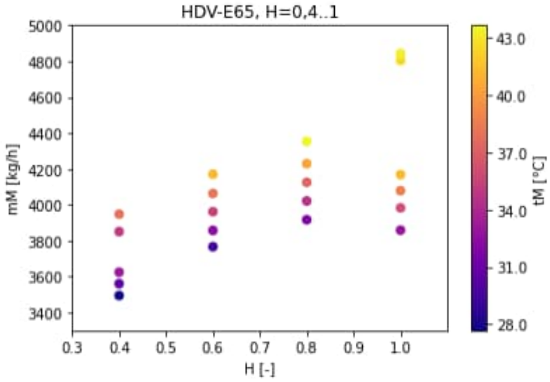


Figure 5: Measured motive mass flow conditions discussed within this work

The measured motive mass flows are shown in Figure 6 as a function of the degree of opening, defined as ratio of stroke to maximum stroke, H.



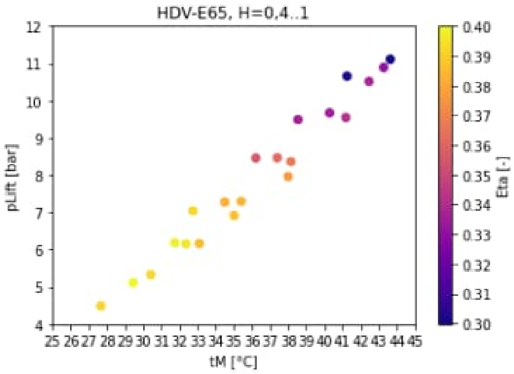


Figure 6: Motive mass flows and temperatures as function of opening degree

Figure 7: Pressure lift and efficiency as function of motive temperature

For a constant degree of opening, the motive pressures vary in 5 bar steps between 80 and 100 bar, whereby the motive temperature is shown on the secondary ordinate in the form of a color scale. The measured motive mass flows are between 3,994 and 4,843 kg/h for motive temperatures between around 28 and 44 °C. For a constant opening ratio, the pressure lift and entrainment show a linear dependence on the motive temperature. Measured lifts and efficiencies according to Elbel as function of the motive temperature are presented in Figure 7. For the measurements discussed within this work, the lift is in the range from 4.5 to 11.1. Thereby the entrainment ratios are in the range of 0.33 to 0.60. As the Figure 3.3 further reveals, the efficiencies are on a high level and in the range from 0.3 to 0.40. The highest values are given with a motive pressure of 80 bara. Here the pressure lift varies between 4.49 and 7.04 bar. Considering an opening ratio of H = 0.8, the measured pressure lift is between 6.2 and 11.1 bar and the entrainment between 0.35 and 0.52. The resulting efficiencies are shown in Figure 8. Based on motive conditions of 80 bara and 32 °C, the ejector offers a pressure lift of 6.2 bar for an entrainment ratio of 0.52 and achieves thus an efficiency of 40 %. Due to the very high pressure lift of 11.1 bar with an entrainment of 0.35, the efficiency equals 30 % for motive conditions of 100 bara and 44 °C.

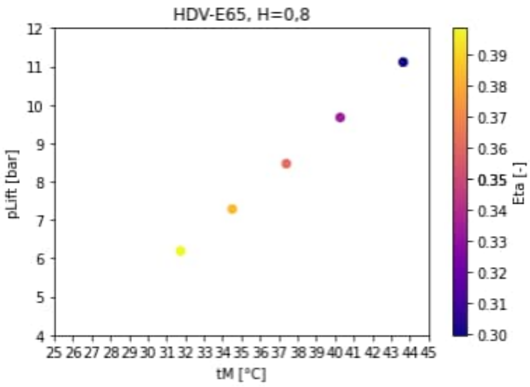


Figure 8: Measured results for H = 0.8

The HDV-E65 showed very good performance values over the entire measured range. The efficiencies exceed the previously calculated efficiencies. The deviation is probably due to the fact that the ejector calculation models were predominately correlated with data from the HDV-E30, -E23 and E16 models, as well as a predecessor model of the HDV-E08. Conditions with low motive temperatures, associated with a significant reduction in potential energy, may constitute a challenge to maintaining high entrainment ratios, especially for Low-Lift applications. Further measurements and investigations are under way for a detailed analysis and performance mapping.

4. CONCLUSIONS

This study shows how emissions in the cooling and heating sector must be drastically reduced in order to achieve climate neutrality. The share of renewable energies in the cooling and heating sector must continue to increase and waste heat must be used. The development in Denmark shows that district heating and cooling in combination with renewable energies is an excellent approach to increasing the efficiency of the energy supply, thus reducing emissions and keeping the grids for the electrical energy supply stable and flexible. The political situation in North America, on the other hand, shows that there are major obstacles to a centralized approach as in Denmark. Consequently, smaller and decentralized solutions with heat pumps are the focus of development there. New solutions in the form of highly efficient compressors and ejectors have been developed for the use of the natural refrigerant R744. Innovative start-ups such as Fenagy and large OEMs use these products. This means that they can be continuously further developed on the basis of operating data and experience. Research projects such as the FORCO2 project, led and coordinated by the DTI, also show that development can be driven forward in collaboration with partners from industry.

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NOMENCLATURE

COP	Coefficient of Performance (-)	mM	Motive mass flow ejector (kg/h)
Eta	Efficiency according to Elbel (-)	OCR	Oil carry over rate (%)
H	Ratio stroke to maximum stroke (-)	tM	Motive temperature (°C)

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