2022

Experimental Investigation of a New Ultra-Low Temperature Refrigerant in an Environmental Test Chamber

Tom Winkler

Melanie Cop

Riley B. Barta

Ullrich Hesse

Winkler, Tom; Cop, Melanie; Barta, Riley B.; and Hesse, Ullrich, "Experimental Investigation of a New Ultra-Low Temperature Refrigerant in an Environmental Test Chamber" (2022). *International Refrigeration and Air Conditioning Conference.* Paper 2330.
https://docs.lib.purdue.edu/iracc/2330

Experimental Investigation of a New Ultra-Low Temperature Refrigerant to Replace R23 in an Environmental Test Chamber

Tom WINKLER*[1], Melanie COP[1], Riley B. BARTA[1], Ullrich HESSE[1]
[1] Technische Universität Dresden,
Bitzer Chair of Refrigeration, Cryogenics and Compressor Technology,
01062 Dresden, Germany
tom.winkler1@tu-dresden.de
melanie.cop@tu-dresden.de
riley.barta@tu-dresden.de
ullrich.hesse@tu-dresden.de

* Corresponding author

ABSTRACT

The EU F-Gas regulation from 2015 and the Kigali Amendment to the Montreal Protocol from 2019 are examples of regulations showing the political will to reduce the use of substances with a high global warming potential (GWP) in refrigeration technology. In the EU, an additional CO_2-quota for manufacturers and distributers of fluorinated substances promotes the transition towards low-GWP refrigerants. This trend then leads to uncertainty regarding the availability of high-GWP substances despite the applicability of certain exceptions to the aforementioned phase-out, such as ultra-low temperature applications (ULT) below -50 °C. Currently, R23 is one of the most common working fluids for ULT applications. Recent developments of new refrigerants such as R469A, R472A and R473A show ongoing research activities to replace the high-GWP refrigerant R23 (GWP = 12400), which have approximately 10% of the GWP of R23. The challenge with many ULT applications are their requirements of high system reliability, a wide temperature range and a limited assembly space, among others. The goal of this work was to investigate the system behavior of a ULT test chamber with an alternative refrigerant to R23.

This paper presents the results of a retrofit of an environmental test chamber originally designed for use with R23 with the refrigerant R473A (GWP = 1800). Theoretical considerations indicate an elevated pressure level and a higher volumetric refrigeration capacity. The necessary modifications to the test chamber for use with R473A were assessed and implemented, and the experimental investigation focused on evaluating the temperature pull-down performance, the minimum temperature achieved in the chamber and the temperature stability at minimum load conditions. The system performance was rated on the pull-down time in reference to the environmental testing standard DIN EN 60068-3-5, the energy consumption and the temperature stability in part load. The investigation concludes with a discussion of the retrofit and further advised system adaptions for the new refrigerant.

Keywords:
ULT cascade system, retrofit, environmental test chamber, R23 alternative

1. INTRODUCTION

Environmental simulation plays an important role in ensuring the quality and durability of technical products. Strict quality requirements must be fulfilled in the fields of the automotive industry, space engineering or medical research, among others. For this purpose, components are exposed to artificially generated environmental conditions in environmental test chambers. This application is characterized by special requirements such as a wide temperature range and rapid temperature changes. For some environmental test scenarios, the chamber has to provide temperatures below -50 °C. The high global warming potential (GWP) refrigerant R23 is currently an established standard working fluid for this temperature range. However, the use of high-GWP refrigerants is becoming more and more restricted due to political regulations. The German climate protection law (Deutscher Bundestag, 2021) or the American Innovation & Manufacturing (AIM) Act (116th US Congress, 2021) are examples for the ambitious climate targets of the next decades. As one part of minimizing the environmental impact, the consumption and production of hydrofluorocarbons (HFCs) should be reduced, according to the Kigali Amendment to the Montreal Protocol (United Nations Environment Program, 2019). The EU F-Gas regulation (European Parliament, 2014) prohibits the use of refrigerants with a GWP of more than

2500. Even though there is still an exception for the ULT applications below -50 °C, a prohibition of those refrigerants will be enforced in the near future. Due to the political will to reduce the use of environmentally harmful substances, the refrigeration industry is facing new challenges. Alternative concepts have to be developed to replace R23 as the mainly used refrigerant for this temperature range. The favorable properties of R23 as a non-flammable refrigerant with a normal boiling point of -82 °C stand in contrast to its high environmental impact with a GWP of 12400 (IPCC (5th AR), 2014). The use of flammable refrigerants, such as R170 or R1132a (Mota-Babiloni et al., 2020), is one alternative to achieve temperatures below - 50 °C. Especially in the field of environmental simulation, the lack of acceptance has slowed the use of flammable refrigerants so far. Recent developments show a trend to use CO_2 as a refrigerant. To achieve a cooling effect below the CO_2 triple-point temperature of -56.6 °C, two possible processes are considered to be promising. The first process is the use of pure CO_2 in a sublimation process and the second is the use of CO_2 as a component of a refrigerant mixture. Even though there are still challenges in establishing a sublimation process, sublimation temperatures of -79 °C (Xu et al., 2021) and -66.3 °C (Iwamoto et al., 2015) have been reached in recent publications on this topic. Other newly developed refrigerants, i.e. R469A (Göpfert et al., 2019) or R472A contain CO_2 as a component in a refrigerant mixture. Those refrigerants are non-flammable and their environmental impact has been greatly reduced. In this context, the use of the new refrigerant R473A (GWP = 1800) is considered to be a promising option. The significant reduction of the GWP by implementing alternative refrigerants in environmental test chambers can contribute to the achievement of climate targets.

In this paper, the feasibility and system behavior of the new refrigerant R473A was investigated in a laboratory test setup. An environmental test chamber in the standard setup with R23 was retrofitted to the operation with R473A. For this purpose, experimental investigations were carried out under various test conditions. The results were evaluated regarding the pull-down speed, the minimum achieved chamber temperature and the temperature stability under minimum load conditions. This led to a comparison of the two refrigerants in order to assess the suitability of R473A as a replacement for R23 in marketable applications.

2. CHARACTERISTICS OF ENVIRONMENTAL TEST CHAMBERS AS AN ULTRA-LOW TEMPERATURE APPLICATION

The environmental simulation has the aim to test the suitability of technical products under designated environmental conditions. Therefore, the quality and durability of the components is analysed during the exposure to representative use cases. This requires the artificial modelling of those conditions in environmental test chambers. Each field of application has its own test regimes, and an environmental test chamber must be able to meet all of these requirements.

This paper focuses only on the refrigeration system of the environmental test chamber. The refrigeration system of an environmental test chamber is subject to special requirements in comparison to a standard refrigeration system, and it operates under varying conditions and has almost no stationary load conditions. Process parameters such as pressure levels and evaporation temperature fluctuate within a given test regime. Therefore, a wide operating range is necessary, and associated control mechanisms are implemented to enable a reliable operation under these varying load conditions. The test scenarios used to evaluate the system performance regarding the various characteristics of each refrigerant will be discussed in this section, and the resulting quantifiable comparison between R23 and R473A will follow.

2.1 Pull-Down Test

The pull-down test is the main experiment to determine the pull-down speed of the chamber temperature for different system setups. The pull-down test is conducted under the specifications of the environmental testing standard DIN EN 60068-3-5 (DIN EN 60068-3-5, 2002).

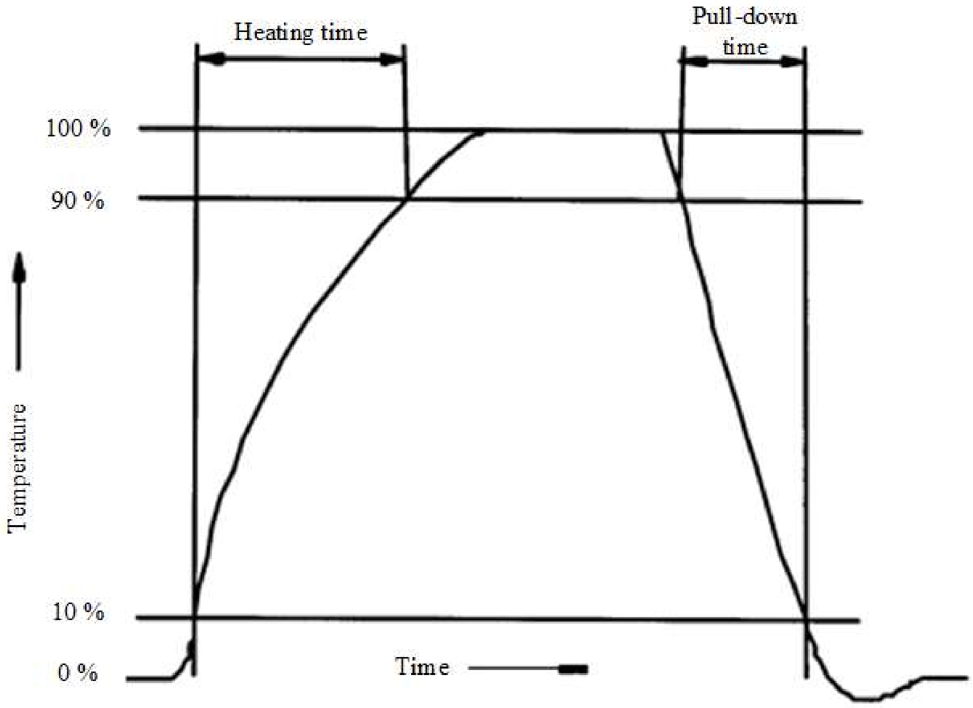

Figure 1: Test regime according to DIN EN 60068-3-5

Figure 1 displays the chamber temperature curve of a complete test regime consisting of a heating phase and a pull-down phase. In the shown load profile, only the temperature drop is relevant for the validation of the refrigeration system. The load profile includes an instant jump of the set temperature from the maximum to the minimum value. The environmental test chamber shifts to cooling mode and the refrigeration system starts to cool down the chamber. Subsequently, the actual chamber temperature approaches the set temperature. While the set temperature jumps from the maximum value (100 %) to the minimum value (0 %), the nominal pull-down speed is determined between 90 % and 10 % of the temperature range, as defined in Equation 1.

$$\dot{T} = \frac{T_{10\%} - T_{90\%}}{t(T_{10\%}) - t(T_{90\%})} \tag{1}$$

In this range, the environmental test chamber operates under full load conditions. As the impact of the control mechanisms is predominant within the transient phase of the temperature range, they can be neglected between 90 % and 10 %. This approach enables a comparability of plants with different control algorithms.

2.2 Minimum Temperature

The minimum temperature achieved in the environmental test chamber is another relevant aspect to evaluate the system performance. To meet the demand of common test scenarios, a minimum chamber temperature of at least -70 °C should be realized and maintained in the laboratory test plant. It is expected that the minimum chamber temperature is greatly dependent on the system configuration, the control parameters and the applied refrigerant.

2.3 Temperature Stability

In addition to a wide operating range, the environmental test chamber should provide a high temperature stability of each set temperature within the temperature range. To meet the demand of common test scenarios, a constant chamber temperature is essential. An accurate adjustment of the control mechanisms enables a high temperature stability. The maximum allowed deviation of the actual chamber temperature from the set temperature is ±0.2 – ±0.5 K. This tolerance interval should be maintained over a duration of at least 120 minutes under steady-state conditions. In addition to the temporal temperature stability, a uniform local temperature distribution in the chamber is also important.

3. EXPERIMENTAL SETUP

To assess the system behavior of the new refrigerant R473A in climate chamber applications, a retrofit of a standard environmental test chamber with R23 was conducted. The laboratory test plant was put into operation to perform comparative measurements for both refrigerants. The investigated environmental test chamber contains a two-stage cascade refrigeration system with an air-cooled condenser. It operates in a temperature range of -75 °C up to + 180 °C and has a chamber volume of 0.28 m^3. The refrigerant R452A was used in the upper cascade stage. While the original setup used R23 for the low temperature stage, it was replaced with R473A in the retrofit setup, thus exposing the system to altered thermodynamic characteristics. To address the new thermal behavior, system adaptations had to be made. Both stages are equipped with reciprocating compressors, which were replaced with models selected through calculations of capacity changes associated with the R23 replacement during the retrofit. While a compressor with increased volume flow was chosen for the upper stage, the low temperature stage used a compressor with reduced volume flow due to the enhanced volumetric refrigeration capacity of R473A. The expansion valves in both stages can be configured in two control modes. Whereas the standard setup operates only with two thermostatic expansion valves (TXV), two additional electronic expansion valves (EXV) were installed during the retrofit. Both options were installed in parallel and can be switched independently for the experimental investigation. The heat exchangers remained unchanged in the current iteration. Figure 2 shows a piping and instrumentation diagram (P&ID) of the underlying refrigeration system, along with the associated measurement types and locations. The environmental test chamber is equipped with a variety of sensors in order to enable the quantification and data analysis necessary to carry out a meaningful experimental comparison of the standard chamber and the retrofitted chamber. The main measurement parameters include pressure, T-Type Thermocouple temperature measurements, Coriolis-effect mass flow meters and electric power measurement.

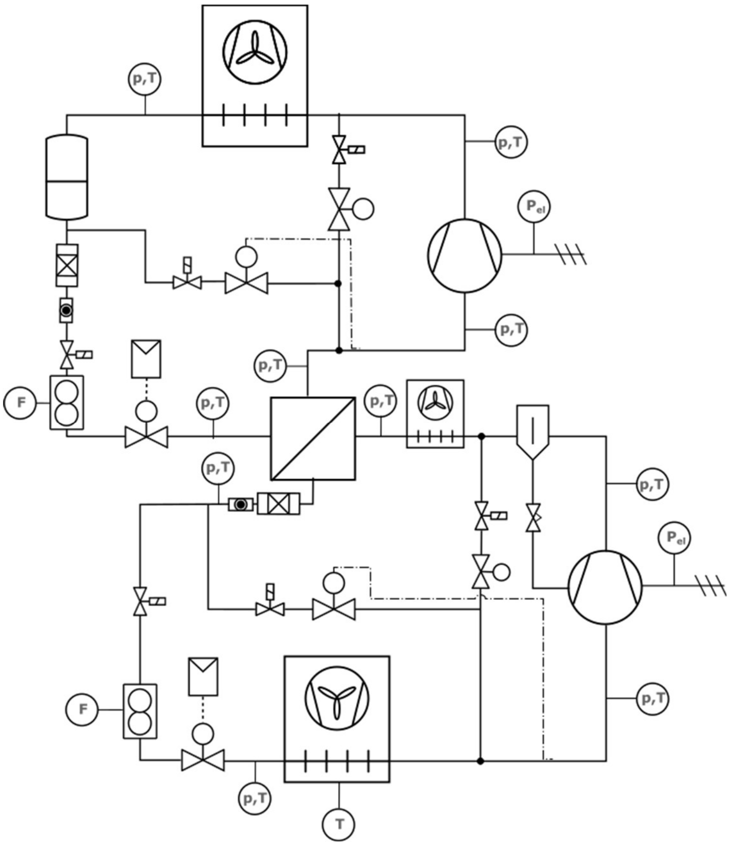

Figure 2: P&ID of the 2-stage cascade refrigeration system

4. RESULTS AND DISCUSSION

After the retrofit adaptations were implemented, the R473A setup was put into operation. Prior to the systematic test regimes, the proper system functionality was validated through a variety of fundamental experiments. The system performance was evaluated by the test scenarios described in chapter 2. The following section displays the detailed setup parameters and the results of those test regimes.

Within the test regimes, different control algorithms were applied for R23 and R473A. Therefore, the transient behaviour differs between the two refrigerants. As a consequence, the comparability of the results is limited to the operation under full load conditions and steady-state conditions. To provide comparable results also for the transient phase, further experiments with similar control algorithms should be conducted.

4.1 Pull-Down Test

The pull-down test is conducted according to the load profile shown in Figure 1. The chamber is heated up to the maximum temperature of 180 °C and kept at this temperature for at least 120 minutes to ensure a uniform temperature distribution. Subsequently, a sudden temperature set point change to -75 °C follows. The test chamber switches to cooling mode and the refrigeration system starts to operate under full load conditions. As the actual temperature approaches the set temperature, the control features are activated and the system transitions to partial load mode. For the underlying experiment, this pull-down speed is calculated with Equation 1 between 154.5 °C and - 49.5 °C. Figure 3 shows the exemplary curves of the chamber temperature behavior for both investigated refrigerants as comparison of the achieved pull-down performance.

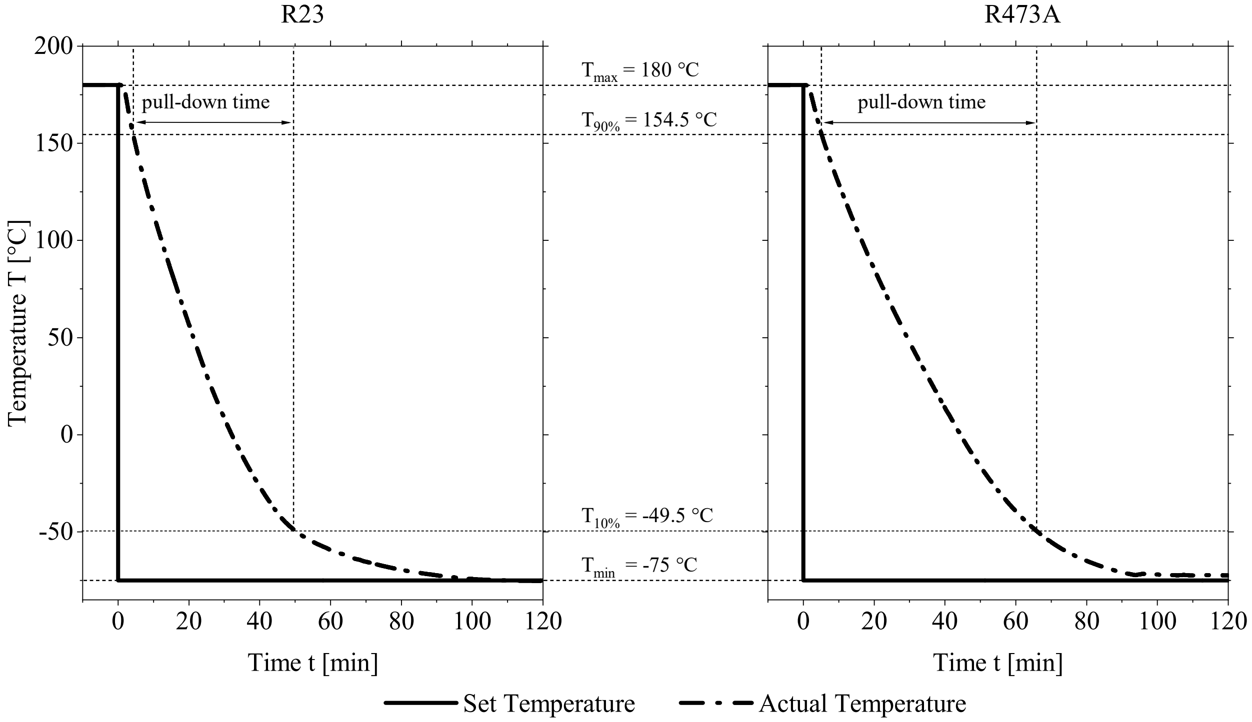

Figure 3: Exemplary temperature curves for R23 and R473A during pull-down testing

For a set temperature of -75 °C, the refrigerants R23 and R473A reach a pull-down speed of 4.5 K/min and 3.4 K/min respectively. Thus, the theoretically higher expected pull-down speed of R473A could not be achieved in the experimental studies. The performance of the new refrigerant was limited by intervening control mechanisms, such as the active injection at the intermediate pressure. Active injection was implemented as a measure to reduce excess compressor discharge temperatures, but as a result reduces the mass flow rate travelling through the evaporator, thus diminished the pull-down performance due to the ensuing reduction of cooling capacity. Therefore, the optimization of the control mechanisms and compressor suction inlet states for R473A will be one of the main objectives for the following experiments. Given that the sources of the control challenges are known and understood, implementation of corrective measures to counteract the negative impact on capacity is a promising next step in the investigation of this topic.

The achieved cooling speed is the main evaluation criterion for the performance of the two refrigerants. Figure 4 shows a comparison of the cooling speed for R23 and R473A at different set temperatures.

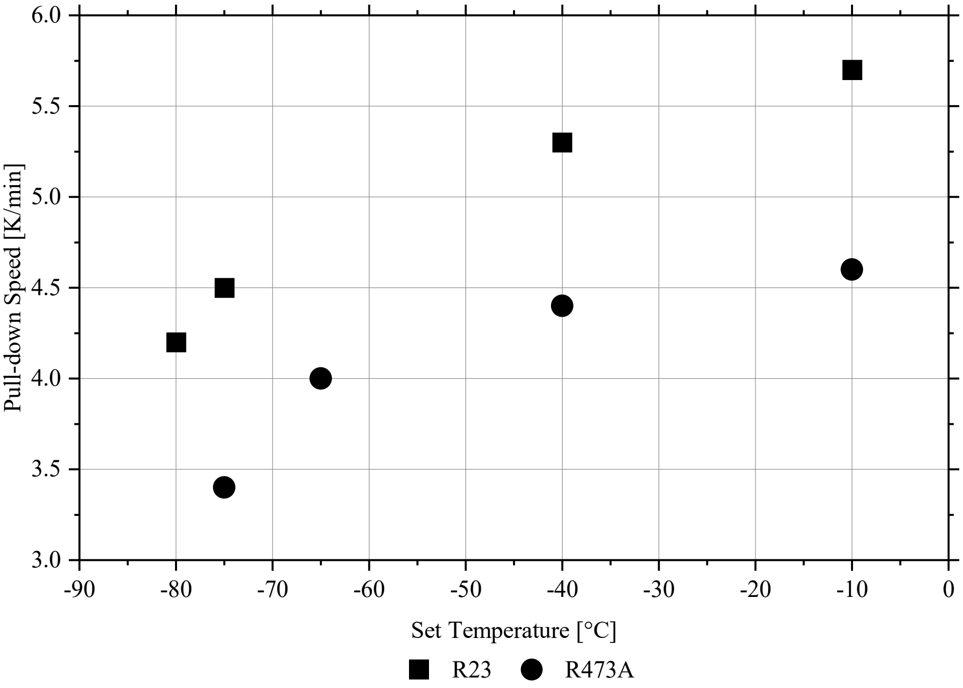

Figure 4: Pull-down speed comparison between R23 and R473A

Each measuring point represents the average cooling speed of a separate pull-down test similar to the shown one in Figure 3. While the pull-down tests with R23 were carried out to a temperature of -80 °C, the minimum set point temperature for R473A was -75 °C. As shown in Figure 3, the temperature drop during the pull-down test is not linear. The temperature decreases slower at lower chamber temperatures, even though the system operates under full load conditions over the relevant temperature range. Therefore, lower cooling speeds were achieved for lower set temperatures. For all pull-down tests, R23 achieved a higher cooling speed than R473A. This result differs from the expectation that the new refrigerant R473A provides at least an equivalent performance as R23. For the set temperature of -75 °C, a cooling speed of at least 4 K/min was desired, thus quantifying the aforementioned. The capacity deficit displayed by the R473A system mainly due to the need for control strategy optimization.

4.2 Minimum Temperature

Besides the pull-down performance, the minimum temperature achieved in the chamber was affected by the new refrigerant. As shown in Figure 3, the achieved minimum chamber temperature differs between R23 and R473A. While the lowest chamber temperature of up to -80 °C was achieved with R23, a temperature of only -73 °C was reached with R473A. Even if the selected set temperature of -75 °C was not reached completely with R473A, the chamber temperature approached steady-state conditions. The current experimental investigations show a variability of the minimum chamber temperature depending on the control parameters and the system configuration. Therefore, more systematic experimental investigations need to be conducted to determine the effect of different influencing factors.

4.3 Temperature Stability

Another important aspect of the experimental studies was the temperature stability under minimum load conditions. Therefore, the chamber temperature was measured under steady state conditions at a set temperature of -65 °C for a duration of 120 minutes. An exemplary chamber temperature curve is shown in Figure 5.

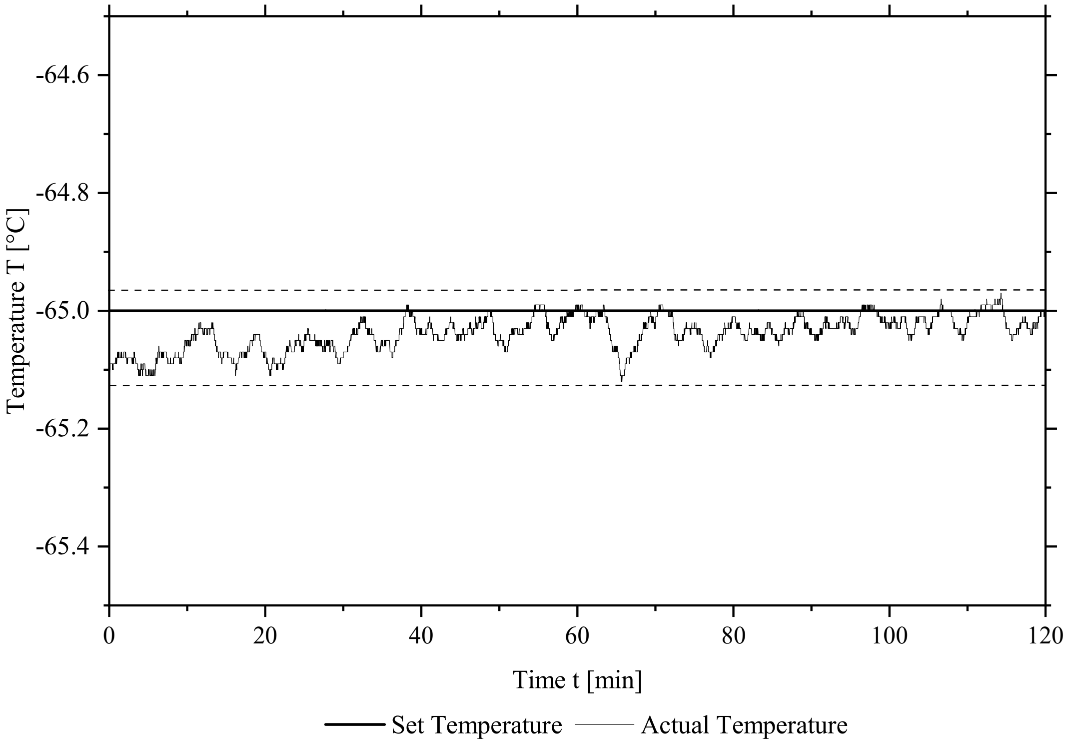

Figure 5: Temperature curve for R473A under minimum load conditions

The temperature curve shows the fluctuating behavior as a result of the active control mechanisms. A maximum deviation of +0.03 °C above and -0.12 °C below the set temperature of -65 °C was determined. The chamber temperature was stable over the entire duration of the experiment and is within the deviation interval of ±0.2 to ±0.5 K. Only one temperature curve was shown as a result of the experimental investigation to provide an example and context. Further investigations are necessary to show the temperature stability over the entire temperature range.

5. CONCLUSION

In the presented study, the system behavior of the refrigerant R473A was investigated experimentally. The setup of an environmental test chamber was changed from R23 to R473A. The retrofit included the modification of the compressor and the expansion valve. The performance of the new refrigerant was rated based on the pull-down test, the minimum achieved temperature in the chamber and the temperature stability under minimum load conditions. The experimental results fulfilled the expectations towards the application of R473A as a new refrigerant in environmental test chambers. The retrofit of the laboratory test plant was conducted successfully. So far, the investigations show that the non-flammable, low GWP refrigerant R473A can be used as a substitute for R23. Compared to R23, the experimental results of R473A show a high temperature stability but a lower performance regarding the pull-down speed and the minimum achieved chamber temperature. Further optimization and changes of the components are necessary to exploit the entire potential of the refrigerant.

NOMENCLATURE

Symbol		
T	temperature	°C
$\dot{T}$	pull-down speed	K/min
t	time	min
Subscript		
max	maximum	
min	minimum	
10%	10% of temperature range	
90%	90% of temperature range	

REFERENCES

116th US Congress (2021). American Innovation & Manufacturing (AIM) Act.

Deutscher Bundestag (2021). Bundes-Klimaschutzgesetz, BGBl. I S. 3905.

Deutsches Institut für Normung e.V. (2002). DIN EN 60068-3-5: Unterstützende Dokumentation und Leitfaden, Bestätigung des Leistungsvermögens von Temperaturprüfkammern.

European Parliament and Counsel (2014). Regulation (EU) No 517/2014.

Göpfert, T., Haack, C., Aydin, M. & Hesse, U. (2019). Kältemittelalternativen für Kältekaskaden bis -80°C. *Proc. Of the Deutsche Kälte- und Klimatagung.* Ulm, Germany.

IPCC 5th AR (2014). *Climate Change 2014: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Mota-Babiloni, A., Joybari, M.M., Navarro-Esbri, J., Mateu-Royo, C., Barragan-Cervera, A., Amat-Albuixech, M., & Moles, F. (2020). Ultralow-temperature Refrigeration Systems: Configurations and Refrigerants to Reduce the Environmental Impact. *International Journal of Refrigeration*, 111, pp. 147-158.

United Nations Environment Program (2019). Kigali Amendment to the Montreal Protocol.

Xu, Y., Mickoleit, E., Thomas, C., Jaeger, A., Breitkopf, C., Hesse, U. (2021). Experimental investigation of a novel cascade refrigeration system with a CO2 sublimation cycle as the lower stage. *International Journal of Refrigeration,* 131, pp. 938-946.

ACKNOWLEDGEMENTS

The presented results were achieved within the scope of a project that was accomplished in cooperation with the Feutron Klimasimulation GmbH through the project number 1130405/1214/05/2020 and is supported by the Thuringian development bank (TAB). The authors express great gratitude to their partners for their financial support.