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DEVELOPMENT AND APPLICATION OF ACCELERATED LIFE TEST CYCLES FOR PERFORMANCE DEGRADATION STUDIES ON WATER-COOLED VARIABLE-SPEED SCREW COMPRESSOR CHILLERS

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ABSTRACT

HVAC&R systems are one of the largest energy consumers in both commercial and residential buildings and their operation is essential to ensure thermal comfort as well as other industrial needs. Within this context, large chillers provide chilled water to condition commercial buildings and the new generation of smart chillers feature variable speed compressors (and/or slide valve mechanisms) that enable active capacity modulation. Understanding mechanisms of degradation and developing models that enable predicting the decrease in performance with respect to the rated values in real time are still open topics in the literature. The overarching goal of this research is to investigate the performance degradation of a 145.9-ton water-cooled variable-speed screw chiller under long term operation and to gain insights into the behavior of the chiller under accelerated life testing. In this paper, an accelerated life cycle testing approach is introduced and then implemented on a dedicated laboratory experimental setup. Preliminary analyses of the chiller behavior after 1,000 *h* operation have been conducted and discussed.

1. INTRODUCTION

Heating, ventilation, air-conditioning, and refrigeration (HVAC&R) equipment is a key technology when it comes to the reduction of the electrical energy consumption of buildings and to meet the goal of the Paris Agreement on Climate Change to reduce global warming. Severe weather conditions with warmer summers and colder winters require more energy for heating and cooling and may lead to an increase by 40% globally by 2030 (IEA, 2018).

The impact of chillers in the building sector is significant despite the fact that chillers are mostly used for commercial applications. It is estimated that chillers provide approximately 60% of the total air conditioning needs for commercial buildings globally (IEA, 2018). Central chillers are used in 3% of the U.S commercial buildings, which accounts for 19% of the total commercial floor space (EIA, 2018). For this reason, it is important to improve the efficiency and operational safety of these systems to reduce energy waste and increase machine lifetime. An enhancement of efficiency and operational safety of chillers can have a notable influence on the global primary energy and electricity consumption.

In the literature, only a limited number of studies deal with analysis of the degradation in chiller performance over time and most of the publications focus on methods for fault detection and diagnosis (FDD). Comstock (1999) performed research on the impacts of faults on chiller performance measures. Based on a manufacturer survey, the following faults were emulated in laboratory testing for a 316.5 *kW* centrifugal chiller unit: loss of condenser water flow, loss of evaporator water flow, refrigerant leakage, refrigerant overcharge, the presence of excess oil, condenser fouling, the presence of non-condensable substances in the refrigerant, and a faulty expansion valve. The results are useful in understanding the impact of these various faults on the chiller system performance at different levels of severeness.

McIntosh *et al.* (2000), created a FDD tool for chillers building on the work of several previous studies, especially on the model and data of a 19,343 *kW*-centrifugal chiller that was set up by Braun (1988). The FDD tool can be used to isolate the fault and associate it to a specific component or component part. Besides the heat exchanger related faults, also compressor related faults were investigated and simulated in a model to test the FDD. To this end, the compressor fault could be separated into internal compressor faults and motor faults.

Beghi *et al.* (2016) proposed a principal component analysis (PCA) for a semi-supervised data driven FDD algorithm to increase the energy efficiency of HVAC&R equipment and reduce the operating cost at the same time. The algorithm detects abnormal operating conditions and characterizes potential faults based on the sensitive variables. The sensitive variables are a collection of features mentioned in elaborations of Comstock (1999), McIntosh *et al.* (2000) and Bendapudi (2004) augmented by additional defined variables. A matrix connects all faults to the related characteristics and the severeness of a fault. For an assessment of the applicability and a tuning of the tool, it was tested using about 200 data sets of air-cooled water chillers with two types of R-134a compressors. One with a frictionless turbo compressor and a cooling capacity of 209 *kW* and another one with a for a screw compressor and a cooling capacity of 220 *kW*.

As the literature review demonstrates, FDD approaches have been widely covered. However, most of the chiller studies primarily focused on detecting the occurrence of actual damage scenarios of components such as a sudden compressor failure or the absence of a sufficient amount of refrigerant charge. Understanding the performance degradation of compressors and detecting emerging behaviors remain open topics in the literature. Knowledge about the performance degradation trends of compressors as well as about the sensitive system variables related to it can be a real gain in the further development of robust and efficient chillers. A performance degradation algorithm based on actual data sets could find its way into predictive maintenance functions but also into prediction models for energy consumption. To take this task forward, an accelerated life test (ALT) has been deployed and implemented on a screw chiller. Based on that work, preliminary analyses are conducted and discussed to expose differences in performance compared to the baseline.

2. SYSTEM OVERVIEW

The investigated system is a variable-speed water-cooled chiller with a screw compressor using the refrigerant R-134a. The chiller is rated with a nominal capacity of a 513.1 *kW* at normal operating conditions and a capacity of 314.1 *kW* in a special ice making mode at lower temperatures. An integrated variable-speed drive (VSD) controls the speed of the compressor load depending by an adjustment of the input frequency. The diagram in Figure 1 shows the cycle components beginning with the screw compressor, which raises the refrigerant pressure from evaporation to condensation level (1→2). After compression, the refrigerant-oil mixture is separated in the centrifugal oil separator (2→3) to avoid the spread of oil into the system and especially in the heat exchangers. The oil is returned to the compressor while the refrigerant is liquefied in a shell-and-tube water-cooled condenser (3→4). The water flows through the pipes while the refrigerant condenses in the shell. The heat exchanger has a discharge gas baffle to reduce the gas flow through the heat exchanger and a sub-cooling part. After subcooling in the economizer plate which is a heat exchanger (4→5), the main part of the refrigerant is then expanded by an electronic expansion valve (5→6) into an evaporator (6→1) that is also a shell and tube heat exchanger. The evaporator is a partly flooded falling-film heat exchanger. The vapor leaves the evaporator through the suction line in the compressor (1). A fraction of the refrigerant is expanded in the economizer (4→7) where the evaporation (7→8) is used for subcooling the refrigerant in the liquid line to raise the system efficiency before it returns to the compressor (8).

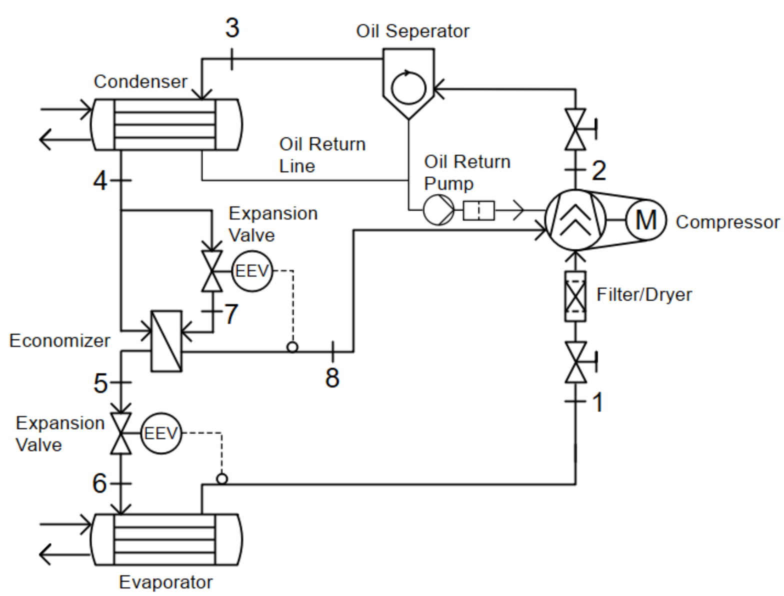

Figure 1: PI-diagram of the internal refrigeration cycle of the chiller

The chiller was integrated in an existing test stand that was redesigned to conduct AHRI 550/590 (AHRI, 2018) performance tests as well as accelerated life tests. The test rig has a close-meshed arrangement of sensors that allows a detailed real time analysis of the chiller data in steady state and transient conditions with fully automated control of the chiller over a wide variety of operating conditions. The ALT test cycles are fully automated through a LabVIEW (2018) VI. The test stand in which the chiller is integrated as well as the designed performance envelope is described in detail by Hoess (2022).

3. ACCELERATED LIFE TESTING APPROACH

3.1 Investigation of ALT Approaches

To track performance degradation over time a comprehensive dataset is necessary, which should cover all sensitive variables of the chiller to allow a time-related analysis of performance changes. Since chillers are industrial products and therefore are usually designed for life spans for 15 years or more, a study in regular operation would demand more time that is available for this project. A solution for that issue is accelerated life testing. ALT can increase the mechanical aging and wear process of a product using extreme, predefined operating conditions and test cycles. This way, the performance degradation can be obtained faster. As there are different possible approaches for ALT cycles and the number of sources for this specific case is sparse, a variety of existing accelerated life test cycles were analyzed to identify the best practical approach, three of them are discussed in the following paragraphs.

Miller and Nelson (1983) introduced one test option is stress based accelerated life testing, where all units run to a failure. Overstress testing can be carried out with high temperature, voltage, pressure, vibration, cycling rate, and load. The stress can either occur as a constant stress level, where an increased failure rate is assumed and the system or the device is run under constant high stress conditions or the stress is applied in steps, where the test unit is exposed to a low stress level initially which is increased step by step after a specified time. The step stress model is useful if the maximum value for a stress test cannot be defined or is hard to estimate. The disadvantage of the step stress mode is that a model is needed to relate the different stress stages to an actual lifetime (Miller and Nelson, 1983). The methodology that Miller and Nelson (1983) use, combines or alternates between different stress types, which is a good way to cover several failures causes in the ALT, while their main aim, the failure of the system, is more problematic for a lifetime estimation.

Pruitt *et al.* (2004) provides a description of a test type in which several cryocoolers were instrumented and underwent 24/7 long-term testing at predefined conditions and steady-state operations that were interrupted by recurring performance tests to compare the current operational data and efficiency with the initially measured baseline data set. The cryocooler was run in this manner until it provided a certain amount of predefined failure data. An accelerated stress testing works with different levels of vibrations and temperatures that affect the system. During the test, the chiller was operated in extreme operating modes that were aiming for a faster degradation of material. This approach is interesting because of the reference measurements that help to analyze a trend of life phase dependent on failures.

Another approach that is closely related to the application of the investigated device was described by Jayatilleka (2018). This methodology works by using predefined repeating cycles, so called seasonal functional usage duty cycles which means that certain cycles or patterns like starts and stops, or total number of revolutions must be identified for the investigated device. Furthermore, a decomposition of the system into subsystems is suggested to identify the components that are prone to failure, *e g.*, a bearing or operating modes that lead to a failure over time *e. g.* start-stop cycles. Jayatilleka's (2018) method helps to define the stress cycles and provides an option for the analysis of the accelerated aging process.

Several other ALT approaches are possible, but none of the reviewed methods provides a step-by-step description of how the accelerated life test for the previously described screw chiller can be conducted. However, they provide a good insight into what needs to be considered for the setup of an accelerated life test and its cycles.

3.2 Definition of the Usage Cycle

The studied approaches clearly show that a usage cycle must be defined based on real operating factors or conditions and if this is not possible, clear assumptions must be made. For HVAC applications, constant usage cycles are hard to define since the application is season and weather dependent. That is why seasonal functional usage cycles (Jayatilleka, 2018) were introduced to flatten out peaks in specific seasonal load modes. The difficulty in considering chiller operations is, that based on the application, their modes and usage cycles offer several degrees of freedom. Dependent on whether a chiller is set up in a single chiller configuration, or in a chiller plant, the operation could be in continuous high load operation, characterized start-stop modes, large load fluctuations, or even a lot of downtime *e.g*., for redundant chillers. Also, the specific implementation of supervisory control within the building automation system can severely impact the annual operating hours of a chiller.

All these factors show that a universal ALT that represents most chillers lives is hard to create. Still, a chiller application case was defined in which the chiller has 5.5 Start-Stop intervals per day. The value comes from the assumption that one year of chiller operation should be simulated in about 12 *weeks* of continuous ALT and one usage cycle should take one hour. To cover a high variety of applications and to load stress on the system, the operating modes within this usage cycles should simulate extreme operating conditions in steady or almost steady state.

To implement an accelerated life cycle testing program, different operating modes were investigated to induce increased mechanical stress on the components, in particular the compressor, without altering the correct operation of the chiller (*e.g*., decrease oil-injection rate, change lubricant oil, among others). The life cycle testing should emulate the field operation of the chiller. Based on these considerations, three major mechanical behaviors have been identified to have significant impact on the chiller operation:

(1) increased friction during the start-up of the compressor
(2) increased mechanical stress due to higher torques at high load operations
(3) decreased lubrication due to decreased differential pressure

These three operating conditions were included in two separate loading profiles which are described in the following sections. During the initial phase of the accelerated life cycle testing, each of the test modes is continuously applied for 2 weeks before switching to the other test mode. Moreover, every 1,000 operating hours, a recurring baseline test is conducted to verify the impact of the repeated loading cycles on the chiller performance. The implementation and control of the repeated loading cycles have accomplished in LabVIEW (2018) by a means of a virtual instrument (VI) that uses time loops for the restart of the cycles.

3.3 Accelerated Life Testing Modes for a Screw Compressor

3.3.1 High Load/Low Head (HLLH)

The first developed usage cycle is the *high load/low head* mode. As the name suggests, this test mode aims at achieving high mechanical stress due to repeated high load operation. The setpoint of the chiller remains at 6.67 *°C* (44 *°F*) and the evaporator inlet temperature target is 12.22 *°C* (54 *°F*). The chiller condenser inlet water temperature was selected specifically low at 15.56 *°C* (60 *°F*). Due to the low head, *i.e*., small difference between the condensation and evaporation pressures, the flow of lubrication oil in the compressor is reduced because the lubrication system relies on this pressure difference and does not have an electrically or mechanically driven oil pump. Every hour, the operation is interrupted by a shutdown of the chiller, followed by an almost immediate startup. This ON/OFF cycling should impose additional wear due to higher mechanical friction at the start up for screw compressors. Figure 2 shows the idealized load curve for the high load/low head-mode.

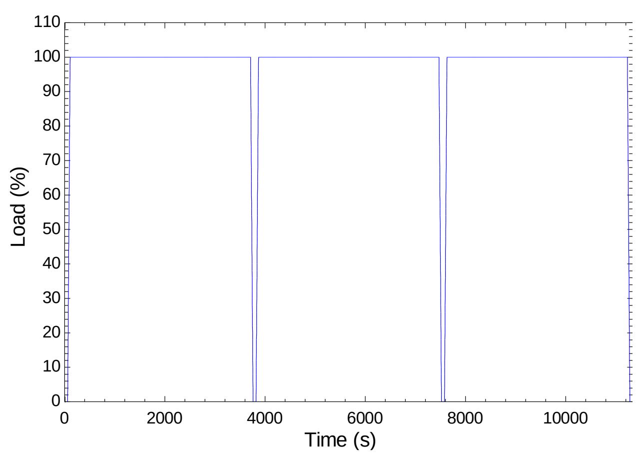

Figure 2: Idealized load curve for *high load/low head* operation

During testing, not all target temperatures could be maintained exactly as shown in Figure 3. A stable operation at exact 100% was not possible to realize in long term operation without continuously increasing operating temperatures. The evaporator inlet temperature fluctuates between 11.39 *°C* and 12.22 *°C* (between 52.5 *°F* and 54.0 *°F*). Therefore, the chiller operates at about 95% with small fluctuations. The condenser inlet temperature was set higher to 18.33 *°C*

(65 °*F*). This was necessary since otherwise, low peaks in the temperature control can lead to a shut down in long term operations. So far, testing data for this mode was processed for 848 *h* (status 05/03/2022). It was found that the OFF-section time could be reduced from the initially planned several minutes to one minute based on evaluation of initial test runs.

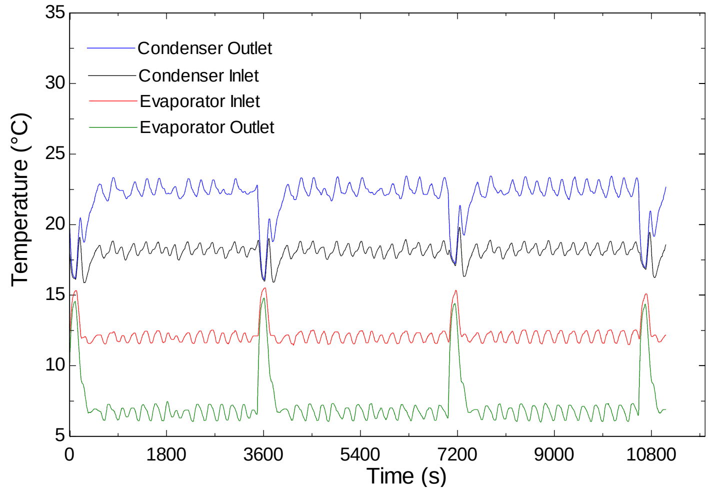

Figure 3: Operating Temperatures in *high load/low head* operation

A check of the oil pressure values (as shown in Figure 4) in comparison to the values obtained under AHRI Standard 550/590 testing operation (AHRI, 2018) indicates that a significantly lower oil pressure existed in the system during the test sets. This supports the initial assumption of additional friction and mechanical wear in this mode.

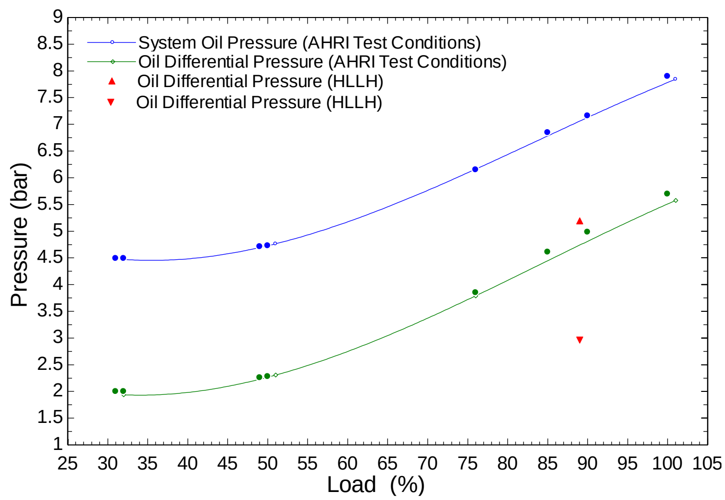

Figure 4: Oil pressure and differential pressure at AHRI Standard 550/590 (AHRI, 2018) test conditions and HLLH test conditions

3.3.2 Low Load/High Head (LLHH)

The second usage cycle that was developed is the *low load/high head* mode. In this operating mode, the compressor experiences an increased friction due to part-load operation along with the stress on mechanical and electrical components resulting from a high-pressure gradient. The minimum load achievable during operation was set equal to 35%. The chiller setpoint remains at 6.67 °*C* (44 °*F*) while the target evaporator inlet temperature is 7.61°*C* (47.5 °*F*). The target temperature for the condenser inlet is 32.22 °*C* (90 °*F*). This condenser inlet temperature is selected to avoid the automatic shutdown of the chiller at temperatures above 35 °*C* (95 °*F*). Like the previous operating mode, the chiller operation is interrupted by ON/OFF-intervals every hour. The idealized operation curve is shown in Figure 5.

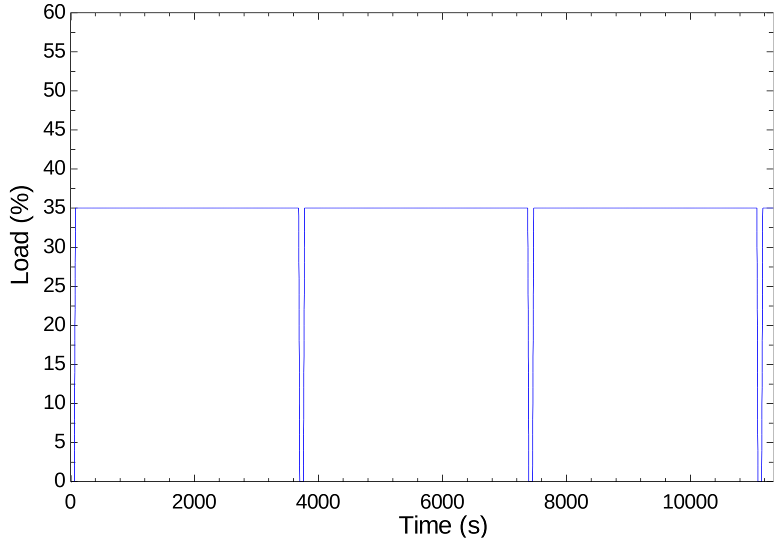

Figure 5: Idealized load curve for *low load/high head* operation

Also in this mode, the parameters needed to be adjusted during the actual testing. The condensing temperature was set to 31.11 *°C* (88 *°F*) in order to avoid a high temperature shut down of the chiller in long term operation. This problem was caused by temperature control peaks. The high condenser inlet temperature caused slightly higher evaporator outlet temperatures of 6,94 *°C* (44.5 *°F*) and the load level needed to be raised for a reliable operation to 40% so the evaporator inlet temperature was 9.44 *°C* (49 *°F*). The fluid temperatures can be seen in Figure 6. So far, this mode of testing was operated for 851 *h* (status 05/03/2022). During early testing, it was found that the hourly OFF intervals could be reduced to a length of 1 minute. This allows enough time to bring the compressor to a stop without producing a too significant temperature change in the water loops.

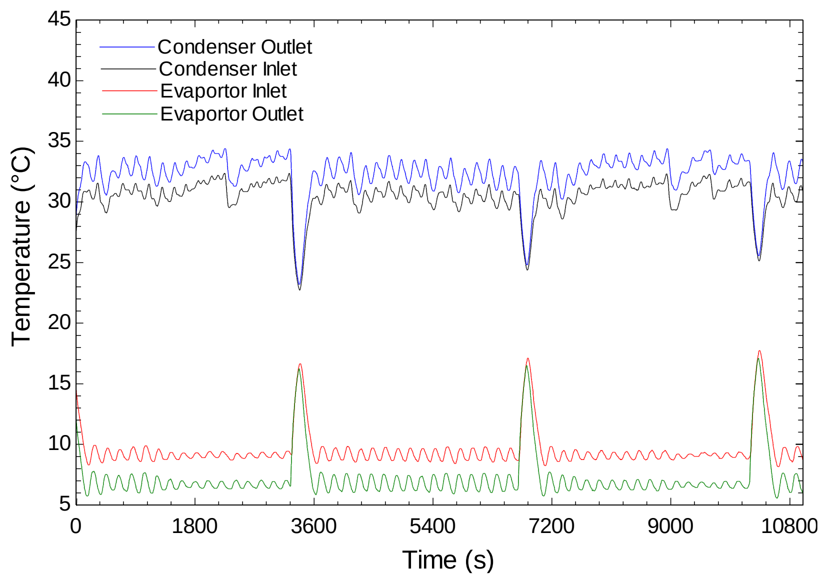

Figure 6: Operating Temperatures in *low load/high head* operation

A plot of the temperatures detected by the motor sensors (see Figure 7) during the LLHH operation mode in comparison with the values obtained under AHRI 550/590 testing conditions at the baseline test and the 1,000 *h*-test clearly shows that the motor temperatures are much higher than under the AHRI performance test (AHRI, 2018) conditions and therefore fulfill the aim of an increased wear of the electrical components over time.

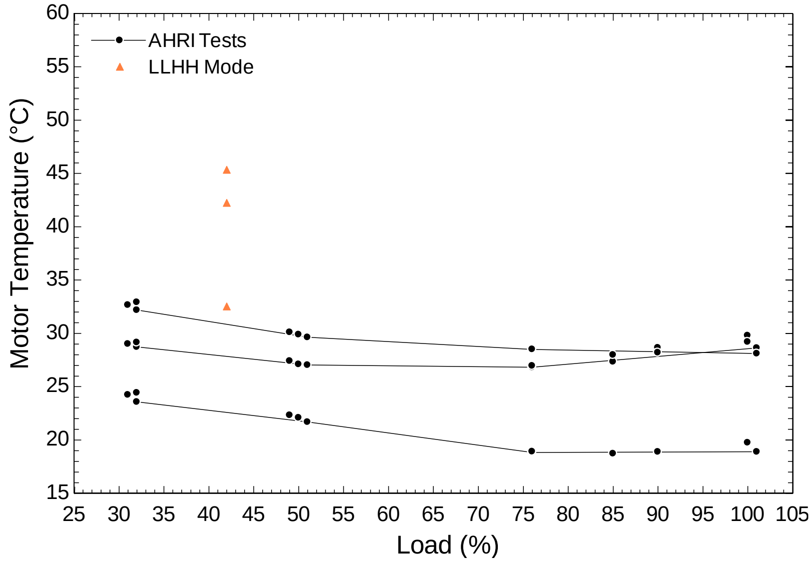

Figure 7: Motor temperature at AHRI Standard 550/590 (AHRI, 2018) test conditions and HLLH test conditions

4. ANALYSIS AND RESULTS

All sensor values that are collected by the test stand as well as internally by the chiller, are logged with a timestamp to make them usable for a comprehensive chiller analysis. At the beginning of the accelerated life testing, a baseline of the chiller according to the AHRI 550/590 (2018) test conditions was measured and evaluated. A performance test according to the standard is repeated in intervals of 1,000 operating hours and the values are compared to the baseline to track a possible degradation. Since the focus of the study is on the performance degradation of the chiller, the performance and directly connected to it, the efficiency of the chiller gets the most attention. The efficiency calculation is described by Hoess (2022).

In Figure 8, the efficiency values that were calculated from the 1,000 *h*-test were plotted over the characteristic line from the baseline tests. A fourth-order polynomial curve fit was applied to create the characteristic line. Almost all efficiency values of the 1,000 *h*-test line up with a very small or no deviation to the baseline. The biggest difference exists for the 100% load efficiency values, but they are still within the tolerance. The sizes of the uncertainty bars in the diagram are determined from the instrumented uncertainties.

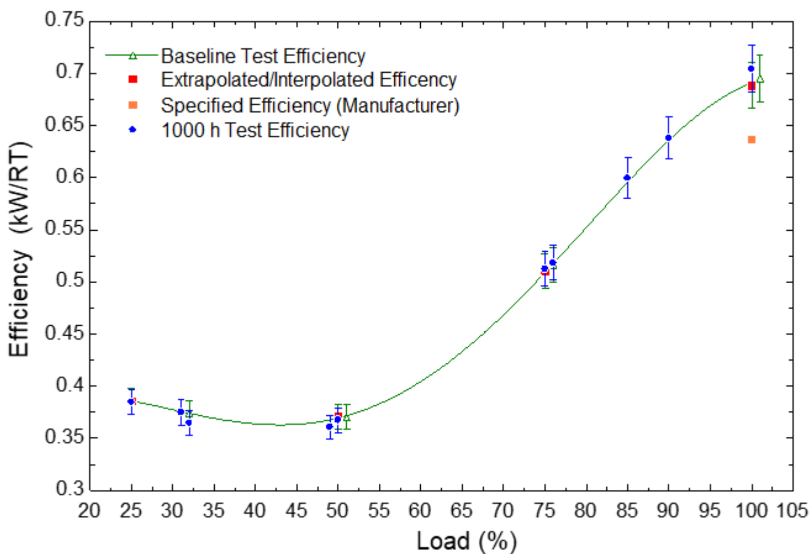

Figure 8: Chiller efficiencies after 1,000 *h* accelerated life testing

To get a better impression of the compressor condition, the overall isentropic efficiency was calculated. Since the screw compressor has an economizer port, the calculation is not as trivial as for regular compressors. In the first step, the cycle was modeled in EES (2020). This step is important to gain the specific enthalpy values of all state points and to calculate the mass flow in every pressure stage (evaporation pressure, condensation pressure, intermediate pressure) via an energy balance of the heat exchangers. The isentropic efficiency was then calculated by utilizing the formula for compressors with economizer port that was presented by Lambers (2008). In equation 1, the power input of the isentropic reference cycle $P_{Isentropic}$ is divided by the power input to the refrigerant in the compressor assuming negligible heat loss which is corrected by the mass flow and entropy change through the economization. It does not include any mechanical and motor efficiencies that would be external to the compression process. For the analysis the measured power draw of the compressor was used directly.

$$\eta_{Isentropic} = \frac{P_{Isentropic}}{\dot{m}_{tot} \cdot h_{disch} - (\dot{m}_{suc} \cdot h_{suc} + \dot{m}_{adm} \cdot h_{adm})} \tag{1}$$

The isentropic power input, $P_{Isentropic}$ needs to be calculated using the specific entropies at the suction port, the admission port and the outlet of the compressor under the assumption that the compression is isentropic the subscript *suc* in equation 2 stands for suction side while *disch* is discharge and *adm* is the admission or economizer line. The schematic drawing in Figure 9 helps to identify the location of the measurements.

$$P_{Isentropic} = \dot{m}_{suc} \cdot \big(h(s_{suc}; p_{disch}) - h(s_{suc}; p_{suc})\big) + \dot{m}_{adm} \cdot \big(h(s_{adm}; p_{disch}) - h(s_{adm}; p_{adm})\big) \tag{2}$$

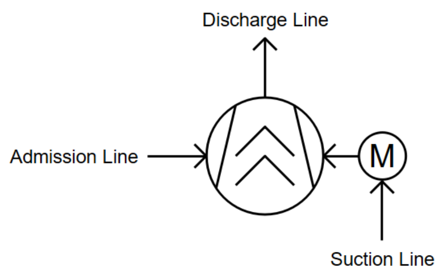

Figure 9: Schematic drawing of the compressor

The overall isentropic efficiency was calculated for the baseline test results. Based on this, a trendline was created that can be seen in Figure 10. The solid dots represent the overall isentropic efficiencies that resulted from the 1,000 *h* testing. The efficiencies are constantly higher than the baseline values. That could result from an initial efficiency increase of the refrigeration machine during a break-in period or is within the uncertainty of the measurements. Since it is the first recurring performance test it is hard to relate a trend to this behavior yet.

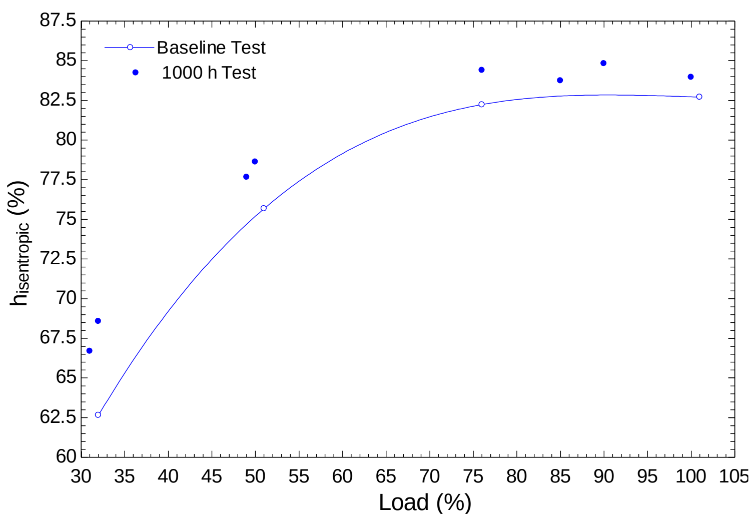

Figure 10: Isentropic compressor efficiencies after 1,000 *h* accelerated life testing

5. CONCLUSION

The aim of the work described in this paper is to perform accelerated life tests for a 513.1 *kW*-screw compressor chiller. The application of the ALT cycles should lead to a faster performance degradation of the compressor since these detailed measurements of performance degradation for chillers is not available in published literature yet. It was important for the test to achieve the performance degradation without a manipulation of the system.

Therefore, different approaches and general requirements for accelerated life testing of refrigeration machines and other mechanical systems were investigated to set up a specified test cycle. Furthermore, test requirements for the chiller and a reference chiller life were clearly defined and the refrigeration system was investigated to figure out potential weak spots that can be used to stress the system. That knowledge was utilized to design accelerated life test intervals and ended in the definition of two different usage cycles which are applied in an alternating scheme. One is the *high load/low head* mode, the second one is the *low load/high head* mode. Each mode aims for different kinds of stress for the mechanical components as well as the electrical components. Once the theory of the test modes was clearly defined, a LabVIEW VI (2018) was set up in a way that both test modes could operate fully automated with a focus on the test accuracy but also on the operational safety of the system. After the commissioning of the test stand for the accelerated life test, initial measurements were taken to prove that the stress on the components is higher than during regular operation. The baseline test values were taken for comparison. It was shown that the test modes work as intended and the automated accelerated life test was started. The two described test modes were changed in intervals of 2 *weeks* so that different kinds of stress could act equally on the system.

It was initially decided to run standard performance tests (AHRI, 2018) after every 1,000 *h* operating interval. This provides an extensive data set of the performance behavior of the chiller and the compressor. Based on the performance test values, the different sensor values are analyzed and further processed to provide insights into the condition of the refrigeration system and its components.

A detailed analysis given by Hoess (2022) investigates various measured values of the chiller such as system oil pressure, oil differential pressure, motor temperatures *etc.* The outcome of this analysis shows a clear trend: after 1,000 *h* run time, no performance degradation can be detected yet. Since the chiller is designed for an operating lifetime of several thousand hours, this outcome in such an early stage of the accelerated life testing is not surprising. The ALT will be conducted further with recurring performance tests. Once a performance degradation is measurable, the trend will be used to validate a computational model.

NOMENCLATURE

AC	Air Conditioning	
ALT	Accelerated Life Testing	
EIA	Energy Information Agency	
FDD	Fault Detection and Diagnosis	
h	specific Enthalpy	(*kJ/kg*)
h	hour	
HVAC&R	Heating, Ventilation, Air-Conditioning, and Refrigeration	
IEA	International Energy Agency	
$\dot{m}$	Mass flow	(*kg/s*)
P	Power	(*kW*)
p	Pressure	(*Pa; bar*)
PCA	Principal Component Analysis	
s	specific Entropy	(*kJ/kg·K*)
VI	virtual instrument	
VSD	Variable Speed Drive	

Subscript

adm	Admission Line/Economizer Inlet
disch	Discharge Line
Isentropic	Isentropic Conditions
Ref	Reference State
suc	Suction Line
tot	Total

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