2016

Design, Build-up, and Commissioning of 350 kW Refrigeration Test Facility for Experimental Investigation of Large Cold Chain Equipment

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ABSTRACT

A new refrigeration facility suitable for experimental investigation of a large variety of cold chain applications has been designed and built from the ground up. The system utilizes a cascade approach and combines two screw compressors in DX configuration cooling ethylene glycol/water (EGW) for low and medium temperature applications. The targeted cooling capacity ranges from 100 kW at -40 ºC to 350 kW at 0 ºC. Both stages are designed for use with R410A. Unlike systems that are installed in commercial environments, this new facility has been fully instrumented, including test sections with visual access, to obtain accurate performance measurements at different ambient temperatures and load conditions. This paper gives valuable insights and lessons learned from the design and commissioning process including controls, start-up, and oil return issues. Good agreement has been observed between actual and target performance for which the refrigeration facility has been designed.

1. INTRODUCTION

In research facilities very often a wide range of cooling capacities and cooling temperatures are needed to provide conditions for testing of various equipment. Stoecker (1998) describes why in industrial refrigeration two stage systems are very common. Among others he listed as advantages of a two stage concept the reduced pressure ratios, lower compressor discharge temperature, lower volumetric flow rate of refrigerant required for the low stage compressor, and improved efficiency attributable to desuperheating of discharge gas of the low stage compressor. To provide cooling for a wide range of operation conditions, a compact two stage refrigeration system has been designed. The described compact system is able to provide cooling capacity at very low evaporating temperatures down to -39 ˚C in the so called cascade operation. Beside this two stage operation with a high stage and low stage refrigeration cycle, the high stage is, in addition to the cascade heat exchanger, equipped with a separate evaporator to cool a secondary fluid. The low stage can also operate as a single refrigeration cycle to provide cooling either by itself or together with the high stage system.

The test facility described in this paper has been fully instrumented to test industrial refrigeration equipment. Unlike other industrial refrigeration systems, the facility is designed to operate at capacities lower than the designed cooling capacity. Thus, different possibilities to modulate the capacity have been installed.

2. FACILITY AND OPERATIONAL MODE

Figure 1 shows a schematic diagram of the test facility which consists of two separate refrigeration cycles (red and blue). A so called low stage (LS) circuit provides cooling capacity at temperatures down t_0 -40 ºC. The high stage (HS) circuit can provide cooling capacity at temperatures down t_0 -15 ºC. In all operational modes heat is rejected through an air cooled condenser (labeled "East condenser" and "West condenser: in Figure 1). The cooling capacity is provided in all three operation modes through a secondary fluid such as ethylene (or propylene) glycol or water for higher evaporation temperatures only. A shipping standard 40 ft. container serves as machinery room for the test facility. Figure 2 shows an early stage of the design process Solid Edge design software was used to plan the arrangement of the components, piping and electrical circuiting this compact setup. Figure 3 shows the air cooled condensers during the design process. Figure 4 illustrates the condensers after the system was built.

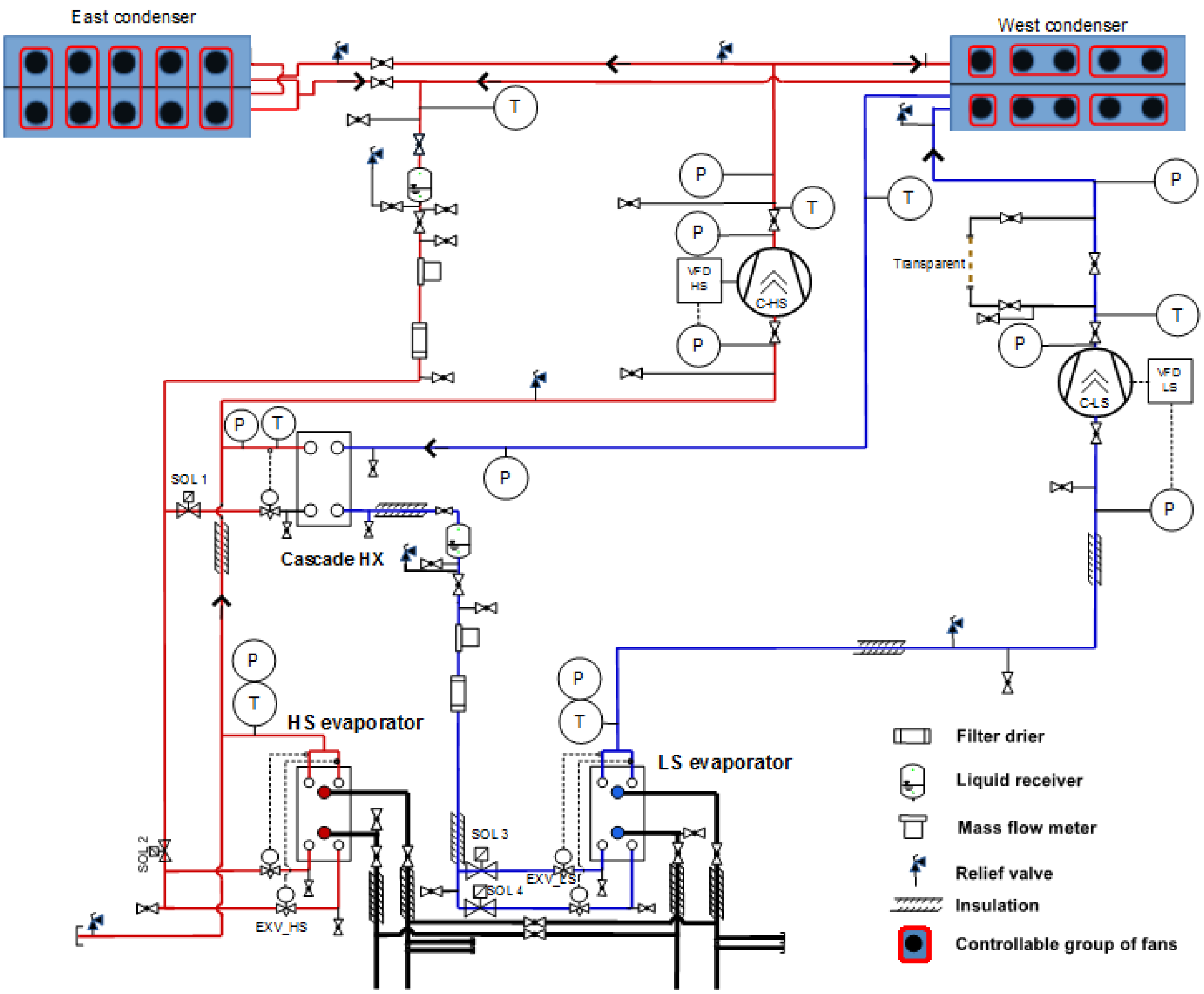

Figure 1: System setup

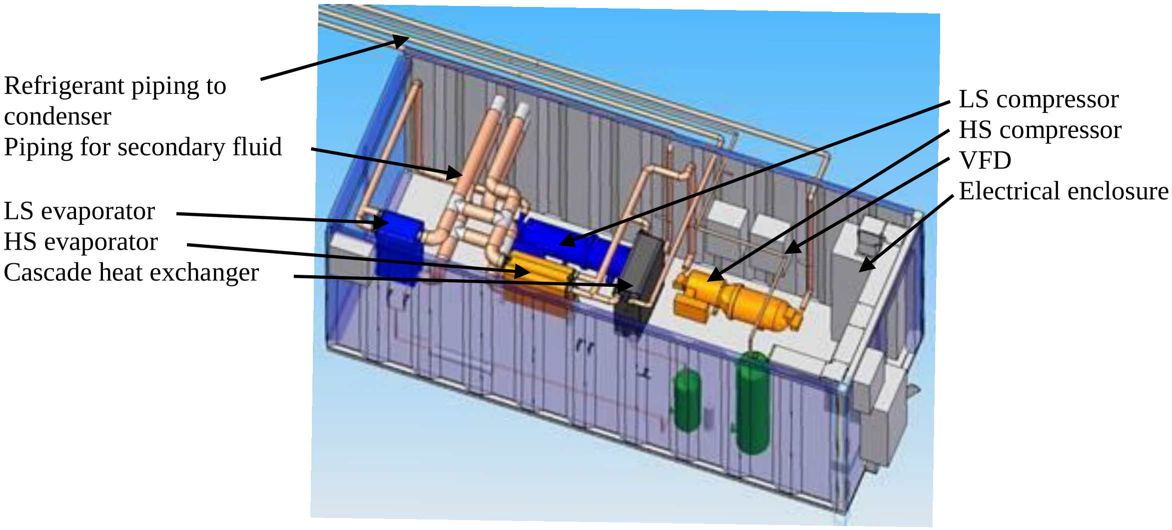

Figure 2: Planning and design of the test facility with CAD

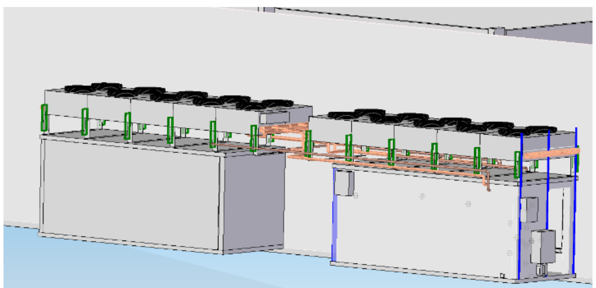

Figure 3: Air cooled condenser on top of container in 3D design

Figure 4: System as built

The main components of the test facility are:

- Two compact screw compressors
- Two air cooled condensers
- Cascade heat exchanger
- BPHX dual circuit evaporator for high stage and low stage

Unlike other industrial systems, this new facility has been fully instrumented. In addition to pressure and temperature measurements necessary for control and safety, mass flow meters based on the Coriolis principle were installed in the low stage and high stage. Also, a transparent section for visual access was mounted in the discharge line to analyze oil flow.

To provide maximum flexibility for testing, the system was designed to operate in three different modes to provide cooling at different temperature levels. The operational modes are:

1. Cascade mode
2. High stage (HS) mode only
3. Low stage (LS) mode only

2.1 Cascade operation mode

To provide cooling at a high temperature lift (t_c/t_0) the system can operate as a cascade refrigeration system to reduce the compression ratio (P_c/P_0) for the compressor. Table 1 shows the pressure ratios for a given temperature lift. In this example, a condensing temperature of 30˚C and an evaporating temperature of -40 ˚C is used to perform the calculation. The intermediate pressure P_{int} was calculated by Equation (1) (Stoecker, 1998).

$$P_{int} = \sqrt{P_c\, P_0} \tag{1}$$

The calculated ideal pressure ratios show that, by choosing a two stage (cascade) system, the compression ratio can be significantly reduced compared to a single stage compression.

Table 1: Pressure ratios for single stage and two stage compression for different refrigerants

Refrigerant	Single stage	Two stage
R410A	10.8	3.3
R134a	15.0	3.9
R717	16.3	4.0

A cascade system consists of two separate refrigeration cycles, the high stage (HS) and low stage (LS). These cycles are thermally connected through the cascade heat exchanger, which provides the condensing capacity for the low stage. The refrigerant chosen for the low stage is R410A. Cooling is provided by the low stage evaporator. This heat exchanger is designed as refrigerant to secondary fluid heat exchanger with two independent circuits on the refrigerant side and one circuit for the secondary fluid. The compressor chosen for the low stage is a screw compressor. After compression, the R410A flows through an air cooled desuperheater and can be, if necessary, desuperheated before it is condensed in the cascade heat exchanger. The desuperheater is part of the West condenser (see Figure 1). From the cascade heat exchanger, the refrigerant enters the liquid receiver. After that, it flows through a filter drier and then through two electronic expansion valves (EXV). Upstream of the EXVs, two solenoid valves (SOL 3 and SOL 4) are installed to allow pump-down mode. The high stage was initially charged for shake down tests with R134a and is now charged with R410A. The refrigerant is evaporated in the cascade heat exchanger to provide cooling for condensing the refrigerant from the low stage. A screw compressor compresses the refrigerant, which is condensed and subcooled in an air cooled condenser before it enters the high stage liquid receiver and filter drier. Upstream of the cascade EXV, a solenoid valve (SOL1 in Figure 1) is installed. After expansion, the refrigerant flows back to the compressor.

2.2 High stage operation mode

Besides the cascade heat exchanger, the test facility is equipped with a separate evaporator for the high stage, the high stage evaporator (HS evaporator). This evaporator is a heat exchanger with two refrigerant circuits and one circuit for the secondary fluid. This configuration allows to provide cooling capacity without running the low stage at the same time.

2.3 Low stage operation mode

Each of the air cooled condensers (East condenser and West condenser in Figure 1) is separated into two circuits. This allows the possibility to use one quarter of the total condenser area for desuperheating. Besides the fact that the desuperheater can increase the efficiency, it allows the low stage to operate without running the high stage compressor or to run in parallel to the high stage to provide even more cooling capacity. In this mode, the desuperheater functions as a condenser for the low stage compressor.

3. CONTROLS AND SAFETY

A commercially available controller designed for industrial refrigeration was used. The controller has built-in features such as PID control, and is capable of monitoring process values like pressure and temperatures and mass flows. To adapt the system to different conditions, various modulation principles were integrated.

1. Capacity control:
    a. Variable frequency drive (VFD) for both screw compressors
    b. Two solenoid valves on each screw compressor
       Besides a seamless control with a VFD, each compressor is equipped with two solenoid valves which allow to change the capacity from 100 % to 50 % in incremental steps of 25 %
    c. Bypass between discharge and suction
2. Condensing pressure control
    a. Controllable condenser and desuperheater fans
    b. Reduction of condensing area by closing one condenser (East condenser)
3. Superheat control by independent expansion valve controller for each refrigerant circuit on the evaporators

In addition to the system controller, which offers safety functionality like protection against high pressure and high

temperature, an additional controller has been integrated to provide redundant and independent protection against system failure. Also, the compressors themselves are equipped with a motor protection devices, which independently monitor the temperature of the motor windings.
During the design process, the compressors have been equipped with oil level switches. A detailed explanation about oil management is given in section 4.

4. DESIGN CONSIDERATIONS AND EXPERIENCE IN OPERATION

Figure 5 and Figure 6 illustrate the predicted performance data for high stage and low stage compressors operating with R410A. The data sheet for the compressors provide capacity data for R134a as well as data for R22/R407c. The data for Figure 5 and Figure 6 were provided by the manufacturer. Based on these values, the designed cooling capacity for the system ranges from 100 kW at t_0 = -40 ºC to 350 kW at t_0 = 0 ºC. The refrigeration components were selected based on the target capacities.

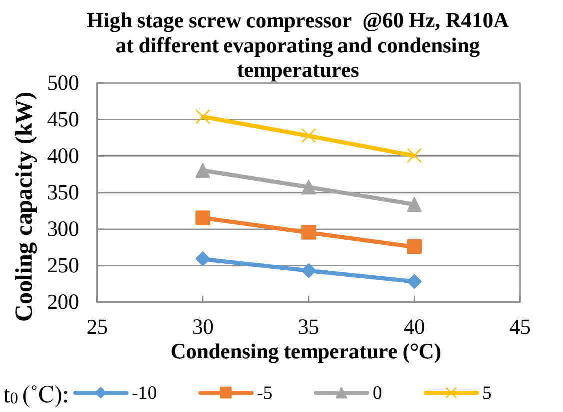

Figure 5: Calculated high stage performance (based on manufacturer data)

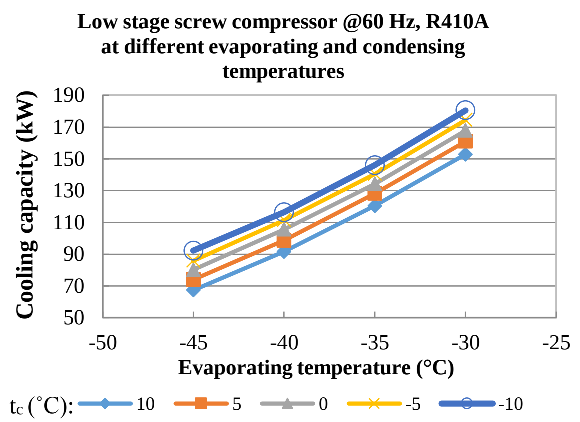

Figure 6: Calculated low stage performance (based on manufacturer data)

For pipe sizing, the velocity range presented in Table 2 was used to ensure sufficient oil return to the compressor and to avoid high velocities in the pipes which can cause high pressure drop.

Table 2: Target velocities for pipe sizing

Section	Velocity (m/s)
Discharge	10…18
Suction	4.5…20
Liquid	1…2.5

Both screw compressors have a built-in oil separators, which are directly flanged onto the compressor. A cross-section view of one of the compressors with the oil separator in presented in Figure 7.

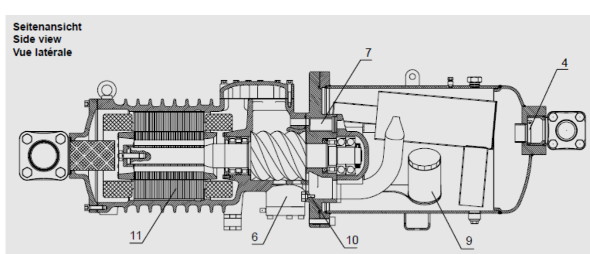

Figure 7: Cross-section view of LS or HS screw compressor (4: check valve, 6:Vi-control, 7:differential pressure relief valve, 9: oil filter, 10: discharge temp. control device, 11: built-in motor) (Bitzer Kühlmaschinenbau GmbH)

Because the compressor does not have an oil pump to ensure oil transport back from the oil separator to the screws and bearings, it is necessary to operate the machine with a pressure difference greater or equal to 4 bar. Assuming that a target evaporation temperature has to be reached (saturated suction pressure is known), the discharge pressure can be controlled as a function of the suction pressure plus 4 bar to ensure a sufficient pressure lift for oil transport. Even with an oil separator, a certain amount of oil will leave the compressor and will be carried with the refrigerant mass flow into the system. In order to investigate the oil flow in the screw compressor discharge line, a parallel bypass for a transparent test section has been installed. This transparent test section makes it possible to visualize the flow of refrigerant and oil leaving the compressor. As described in section 3, the system is designed to modulate the capacity by changing the frequency of the compressor, turning on and off solenoid valves etc. All of these options reduce the mass flow Therefore, a certain velocity is necessary to carry oil from the system (pipes, heat exchanger, etc.) back to the compressor. Oil can be easily trapped in the evaporators if the system runs with a reduced mass flow. Thus, evaporators with two refrigerant cycles have been selected. At low capacity, one electronic expansion valve or the solenoid valve located upstream can be closed. The evaporator operates then with a lower efficiency but with a higher velocity in one circuit. This operation ensures sufficiently high velocities in the heat exchangers and, therefore, ensures sufficient oil return. However, the shakedown and first tests showed that it can be helpful to increase the compressor speed after testing to further improve oil return.
The test facility provided cooling capacity in the following operation modes:

- High stage with R134a in HS operation mode
- High stage with R134a and low stage with R410A in cascade operation mode
- High stage with R410A in HS operation mode
- Low stage with R410A in LS operation mode

4.1 High stage with R134a in HS operation mode
Running the high stage compressor with R134a allowed a simple performance comparison with the manufacturer's data presented. The manufacturer provided catalog data (Bitzer Kühlmaschinenbau, 2015) for cooling capacity and power consumption. Figure 8 and Figure 9 illustrate performance data for high stage compressor with R134a at two different evaporating temperatures. The presented data confirmed good agreement between catalog and measurements for cooling capacity and power consumption. A good agreement between catalog data and measurement could be archived for cooling capacity as well as power consumption of the compressor.

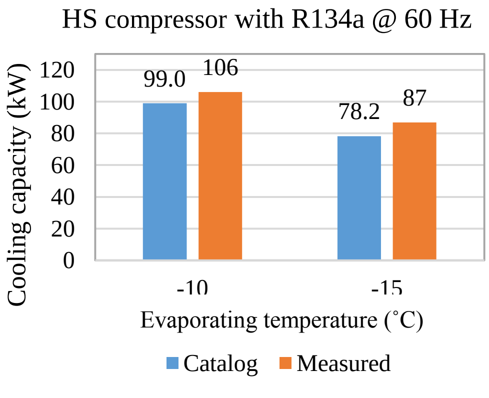

Figure 8: Cooling capacity of HS compressor with R134a at different evaporating temperatures (t_c: 35 ˚C)

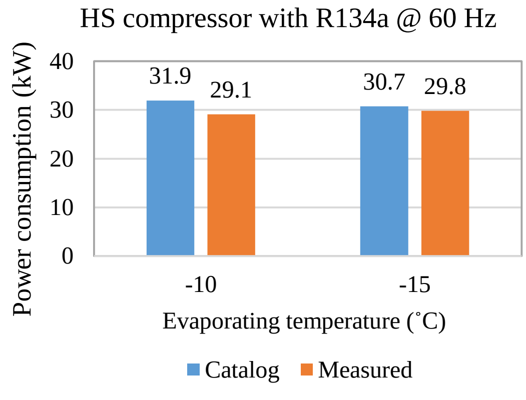

Figure 9: Power consumption of HS compressor with R134a at different evaporating temperatures (t_c: 35 ˚C)

4.2 High stage with R134a and low stage with R410A in cascade operation mode
The test facility operated in cascade mode at -35 ˚C evaporating temperature for shakedown tests and testing of ammonia heat exchangers. The necessary heat for the evaporator was provided by a pump cart equipped with controlled electrical heater ($\dot{W}: 100\ kW$), controlled pump and mass flowmeter (Micro Motion CMF 300) as well as temperature measurements and power measurements for both heater and pump. The cascade system provided the capacity to the system. Figure 10 illustrates performance results in cascade operation at an evaporating temperature of -30 ˚C. Figure 11 presents the performance results in cascade operation for an evaporating temperature of -39 ˚C.

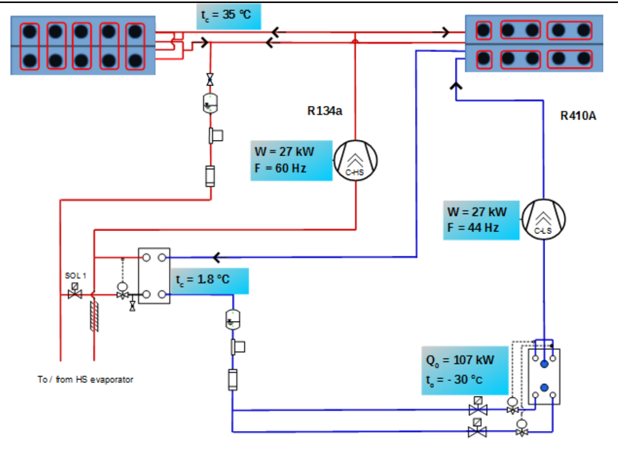

Figure 10: Performance of cascade system with R134a (HS) and R410A (LS) @ t_0: -30 ˚C; t_c: 35 ˚C

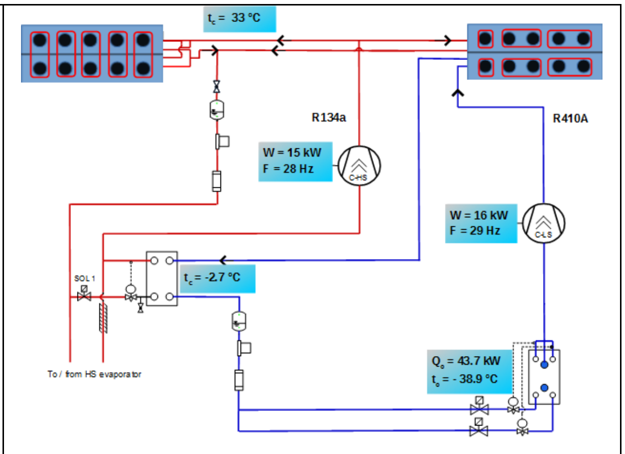

Figure 11: Performance of cascade system with R134a (HS) and R410A (LS); t_0: -39 ˚C; t_c: 33 ˚C

For both tests, the high stage was charged with R134a and the low stage with R410A. The measurement of cooling capacity in Figure 10 is the sum of 100 kW from electrical heater and power of the pump.

4.3 High stage with R410A in HS operation mode

In order to increase the capacity of the test facility, the refrigerant of the high stage compressor was replaced with R410A. As expected the cooling capacity increases significantly by using R410A instead of R134a. The measured and calculated cooling capacities for the high stage compressor with R410A are presented in Figure 12. The described test facility provided the cooling capacity at the desired evaporation temperature for a commercial refrigeration system. Also this data showed a good agreement between measurement and predicted capacity.

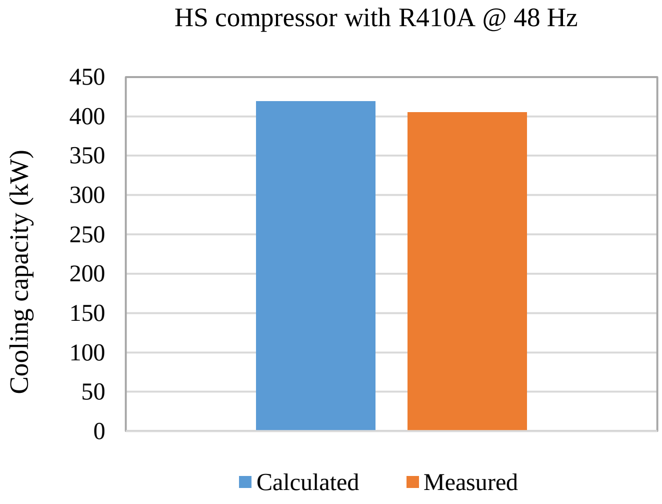

Figure 12: Cooling capacity of HS compressor with R410A at t_0: 14.6 ˚C, t_c: 40 ˚C

6. CONCLUSIONS

This paper presented design consideration and experimental data as well as insights from the design and commissioning process for a two-stage refrigeration system in industrial scale. In comparison to state of the art cascade systems, the presented design allows the system to operate in two additional configurations, the high stage mode only and the low stage mode only. All three modes can provide cooling capacity in single operation within a wide range of cooling capacity. The compact designed test facility is equipped with additional instrumentation like mass flow meters. This design allows the facility to provide cooling for testing industrial equipment. In addition, a test section with visual access is installed to investigate e.g. oil flow in refrigerant pipes. In order to provide a wide range of cooling capacity, several options for capacity control are included in the design. If the system operates at low mass flows (low capacities), special attention must be paid to the oil return at such conditions. The commissioning process confirmed that at low compressor frequencies, oil can be trapped in the system. The evaporators are designed for approximately 480 kW (high stage) and 210 kW (low stage), holding a significant amount of oil during such operating conditions. With the two-circuit design, the velocity in the heat exchanger can be increased as long as one heat exchanger circuit for heat transfer is sufficient. However, oil can be carried back from the system by increasing the compressor speed at the end of a test run. The test facility has been run in all three of the presented operation modes. The presented measurements show good agreement between the catalog/calculated and measured data. The facility is ready to test industrial and commercial refrigeration equipment at cooling capacities from 100 kW at t_0 = -40 ºC and 350 kW at t_0 = 0 ºC.

NOMENCLATURE

F	Frequency	(Hz)
P	Pressure	(bar)
$\dot{Q}$	Capacity	(kW)
t	Temperature	(ºC)
$\dot{W}$	Power	(kW)

BPHX	Braze plate heat exchanger
CAD	Computer Aided Design
C-HS	High stage compressor
C-LS	Low stage compressor
HS	High stage
LS	Low stage
P	Pressure measurement
T	Temperature measurement
VFD	Variable Frequency Drive

Subscript

c	condensing
0	evaporating/cooling

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Bitzer Kühlmaschinenbau GmbH (2015). Applications Manual. *Semi-hermetic compact Screws, SH-150-2*.

Stoecker, W. F. (1998). *Industrial Refrigeration Handbook*. New York: Mc Graw-Hill.