High-Performance Rotary Screw Compressor Test Stand

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High-performance Rotary Screw Compressor Test Stand

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ABSTRACT

A new high-performance test stand tests both constant speed and variable speed semi-hermetic rotary screw R134A water chiller compressors ranging from approximately 250 to 600kW rated refrigeration capacity. The stand produces rapid post-production functional tests with excellent accuracy, higher measurement accuracy laboratory-quality tests, and also manually-directed tests of any duration. All tests include startup, warmup and steady state data recording at three operating conditions (typically full load displacement, intermediate load and unload). Some compressor models additionally perform an oil shuttle control valve test.

The automatic test sequence requires operator intervention only to mount and connect the Unit Under Test (UUT), scan barcodes and start the test. Following test completion, the operator disconnects and removes the UUT. A workstation computer prints and saves a comprehensive test report automatically.

Two test stations increase throughput by allowing a UUT that has completed testing to be reclaimed and unloaded, and a new UUT to be loaded and evacuated on one station while a third UUT is running a test on the other station. A Programmable Automation Controller (PAC) monitors and controls the refrigerant circuit and the UUT variable frequency drive as well as auxiliary equipment such as lube oil, vacuum and reclaim systems. Other integrated controls include a touchscreen operator interface and three personal computers (PCs).

1. INTRODUCTION

The test stand has one refrigerant circuit and two test tables or stations. While a test is active on one station, lockout valves isolate the inactive test station from the refrigeration process to enable the inactive compressor to be reclaimed, vented, disconnected, and removed from the station. Then a new compressor can be positioned, connected and vacuum purged to prepare it for testing.

Two customized shipping container enclosures, stacked, contain most of the refrigeration process equipment. The two test stations are located on the ground floor outside the lower enclosure along with an adjacent equipment area containing reclaim equipment, oil storage and an access stairway to the upper level. The upper enclosure level features an adjacent equipment deck containing electrical transformers, motor control center, compressor variable frequency drive, compressor power contactor and electrical distribution panels.

The test stand Programmable Automation Controller (PAC) monitors and controls the refrigerant circuit, lube oil system, vacuum system, reclaim system and the UUT variable frequency drive. The PAC also controls UUT start/stop, speed and load/unload functions, and executes automatic or semi-automatic tests. Other controls include a touchscreen operator interface and three personal computers (PCs), including an engineering workstation, a data historian and a vibration monitoring and analysis system.

2. REFRIGERANT CIRCUIT

2.1 Thermodynamic process

Refrigerant compressors may be tested using a calorimeter, wherein the entire refrigerant flow condenses at the desired high pressure condition, and the throttled liquid evaporates to the desired suction conditions. These systems can have relatively slow thermal response, and can be difficult to control precisely.
Since a compressor test stand needs to produce no net heat transfer effect, faster response can be obtained by simply throttling the hot gas from the discharge pressure to the suction pressure. In order to control both discharge and suction conditions independently, the throttling process needs to occur in two stages, establishing an intermediate pressure. In this test stand the refrigerant circuit has three pressure zones (high, intermediate and low) separated by throttle valve stations. A small portion (10-30%) of the refrigerant gas from the intermediate pressure zone passes through a condenser, and the resulting liquid is injected into the low pressure zone, to offset heat added by the UUT compressor and to control suction superheat temperature.


Pressure-enthalpy diagram, Figure 1, illustrates the test stand thermodynamic process for a typical compressor. Figure 2 shows a simplified process diagram. Table 1 shows typical operating conditions.

![Pressure-Enthalpy Diagram](image1)

**Figure 1:** Pressure-Enthalpy Diagram

![Simplified Process Diagram](image2)

**Figure 2:** Simplified Process Diagram
Table 1: Typical operating conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated suction temperature (°C)</td>
<td>4.5</td>
</tr>
<tr>
<td>Suction superheat (°C)</td>
<td>8.33</td>
</tr>
<tr>
<td>Suction pressure (kPa abs)</td>
<td>350</td>
</tr>
<tr>
<td>Saturated discharge temperature (°C)</td>
<td>24-57</td>
</tr>
<tr>
<td>Discharge pressure (kPa abs)</td>
<td>640-1550</td>
</tr>
<tr>
<td>Refrigerant mass flow (kg/min)</td>
<td>23-230</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>2.0-4.5</td>
</tr>
<tr>
<td>Intermediate pressure (kPa abs)</td>
<td>550-700</td>
</tr>
<tr>
<td>Refrigeration capacity range (kW)</td>
<td>60-600</td>
</tr>
</tbody>
</table>

Figure 3: Refrigerant Process Schematic
2.2 Test station
Figure 3 illustrates the test stand refrigerant circuit schematically.

Both test stations are functionally identical. Solenoid-controlled pneumatic-actuated ball valves isolate each test station from the refrigerant circuit and from the various auxiliary service circuits. Pneumatic and electrical interlocks ensure that the valves remain correctly aligned during a test run, as well as during purge/reclaim operations and when the test station is off-line.

Test station suction piping includes a particulate filter, vacuum gauge, redundant precision pressure and temperature sensors and low pressure safety switch. Discharge piping includes pressure safety valve, redundant performance sensors, high pressure and high temperature safety switches.

2.3 Compressor discharge (high pressure) circuit
The refrigerant vapor, with entrained oil, flows from the compressor discharge of the respective test station into a custom-designed separator vessel, with both centrifugal and chevron vane elements and a separation efficiency of 99.9% or better across the entire operating range.

The discharge pressure control station includes two servo-electric globe-type control valves, each with equal percentage flow characteristic, installed in parallel. The smaller valve has a maximum flow coefficient approximately 5% of that of the larger valve. The valves always operate in tandem, and each has very fine positioning resolution (±0.2%). The control algorithm modulates the large valve during a transient to control discharge pressure, while the small valve remains in fixed position in the middle of its operating range. When process conditions become stable, the control algorithm fixes the large valve and enables the small valve to control pressure. In this way the control station operates with very fine resolution over a wide range of flow and pressure conditions.

2.4 Intermediate pressure circuit
Downstream of the discharge pressure control station, a Coriolis type flowmeter measures vapor mass flow rate. Nominal flow measuring accuracy at full load (high flow) is ±0.35% of rate, but accuracy degrades to about ±0.8% at the lowest flow conditions. Since this test stand is equipped with only one mass flow meter and there is no independent confirming meter, the test stand does not conform to ANSI/ASHRAE 23.1, although it does conform in all other respects.

A pressure transmitter and temperature sensor measure process conditions in the intermediate pressure zone of the hot gas loop, and a pressure safety valve protects all downstream piping and equipment.

2.5 Hot gas bypass circuit
The hot gas bypass circuit includes a suction pressure control station and desuperheater station. The suction pressure control includes two servo-electric globe type control valves installed in parallel, similar to the discharge pressure control.

“Desuperheating” is the process of injecting a volatile liquid phase directly into a superheated vapor phase. The gas cools, and the heat given off by the gas vaporizes the liquid. There is not necessarily any heat exchange with the surroundings. If all goes well, the desired result of desuperheating is a cooled vapor stream that remains somewhat superheated.

To obtain tight control and fast response in a compact test stand, it is desirable to complete the vapor/liquid mixing as quickly as possible. This test stand uses an in-line flange-mounted desuperheater device that contains an array of venturi nozzles and a liquid nozzle that sprays upstream. Acceleration and deceleration of the gas/liquid mixture through the venturis, together with rotation of the venturi streams, thoroughly shears and mixes the liquid droplets with the gas to ensure complete vaporization within a short pipe distance.

This application requires two desuperheater elements, one smaller (50mm pipe size) and the other larger (75mm), to cover the entire range of flow conditions. For proper vaporization, it is necessary to maintain a minimum vapor velocity and also to maintain a minimum spray nozzle pressure differential for good liquid atomization. At low load
settings, all compressors use the small desuperheater only. Most compressors at higher load settings use the larger desuperheater only, while the largest compressors use both desuperheaters operating in parallel.

Injection (suction superheat temperature) control uses a combination of liquid throttling valves and a variable speed pump operating in series. At low flow conditions, condenser pressure is sufficient for injection and the pump idles at low speed. At higher vapor flow rates, the liquid control valves open wide and pump speed modulates to control suction temperature.

2.6 Condenser circuit
The condenser, a conventional shell-and-tube heat exchanger, uses chilled water from the plant utility and operates at approximately 18°C and 545kPa absolute pressure. The condenser does not connect directly to the intermediate pressure zone, but rather connects through a servo-electric globe control valve. As a test begins, this valve remains closed to isolate the condenser from the intermediate pressure zone. This ensures that condenser pressure stays sufficiently high so that the liquid refrigerant remains subcooled, even while intermediate zone pressure may fall quite low. Later during the test, as discharge pressure rises, the valve controls intermediate zone pressure, allowing condenser pressure to vary.

The receiver tank stores a working volume of liquid refrigerant. Receiver level is not controlled but varies during a test, depending upon the amount of refrigerant elsewhere in the circuit. The subcooler heat exchanger reduces liquid temperature approximately 5 to 10°C, to ensure that the liquid remains sufficiently subcooled to prevent injection pump cavitation.

3. AUXILIARY SYSTEMS

Lubrication oil – This system filters, measures and, if desired, cools the lube oil, and delivers the oil from the separator to the main oil port of the active UUT. Oil circulates due to the pressure difference between the discharge oil separator and the (lower) back pressure at the UUT oil port, just as it would in a chiller assembly. The lube oil system also includes two small motor-driven pumps with flow meters that inject small quantities of oil into the UUT main and rotor oil ports prior to a test run. The oil separator stores a significant quantity of oil in an integral heated reservoir. A small motor-driven pump automatically replenishes oil from a bulk container between tests.

Vacuum – A two-stage vane type vacuum pump removes air from the UUT stations after UUT hookup and before introduction of refrigerant gas into the test station piping. The system may also be used to evacuate filters or to evacuate the entire test stand after the refrigerant loop has been opened for service.

Reclaim – This system removes refrigerant gas from the UUT stations after test, condenses and purifies the refrigerant to ARI-700-95 standards and returns the refrigerant liquid to the test stand receiver. The system may also be used to reclaim filters or to reclaim the entire test stand into storage cylinders prior to servicing. The system has two other essential functions. During cold weather (ambient temperature can reach as low as 10°C) the reclaim system automatically collects condensed refrigerant from the test stand suction piping and returns the liquid to the receiver. Also automatically, as required, between tests, the reclaim system draws vapor from the top of the condenser and separates and removes air and other non-condensable gases from the refrigerant.

The system includes a packaged reclamation machine, which is capable of reclaiming from pressures as high as 1,500kPa absolute down to low pressures of about 35kPa absolute (250 Torr). At this level of vacuum, about 4% of the refrigerant charge would remain in the piping. To obtain higher vacuum, the reclaim system includes an auxiliary vacuum pump that recovers all but 0.25% of the refrigerant, at about 2 kPa absolute (15 Torr).

Ventilation – a motor-driven fan operates continuously to draw fresh air into the equipment enclosures and to exhaust the air to outdoors, for equipment cooling and to prevent the buildup of refrigerant gas in case of a minor leak. Sensors in various locations within and surrounding the test stand detect any refrigerant leak and trigger an alarm and ventilation purge.

Electrical power – A motor control center includes combination starters and variable frequency controllers for auxiliary devices. A step-down transformer with electrostatic shielding feeds clean power to loads with high harmonic
content, such as computers and electronics with switching type power supplies. A second step-down transformer feeds other motors and general purpose loads.

A custom packaged variable frequency drive system, switched through vacuum contactors, delivers electrical power to the two test compressors. The vacuum contactors are mechanically and electrically interlocked with a key control system that prevents a contactor from being closed unless the other contactor is open and the corresponding test compressor motor terminal box is closed and locked.

4. DATA ACQUISITION AND CONTROL

The data acquisition and control system includes an interconnected network of devices as follows:

- Programmable Automation Controller (PAC), with multiple input/output chassis, and local area network communication – sequence control, safety interlocks, data measurements
- Pendant-mounted touchscreen panel – operator interface
- Cordless barcode scanner – UUT model and serial# entry
- Personal computer #1 (engineering workstation) – graphic display, test reports, VFD communication, test profile management
- Personal computer #2, data recording
- Personal computer #3, vibration monitoring and analysis system
- Electrical power analyzer
- Motor management relay – test compressor motor protection
- Precision temperature scanner – suction temperature measurement

PC#1 interfaces with the proprietary variable frequency drive (VFD) through an RS-485 network connection. Communications software bridges among the PAC database, the PCs and the smart instruments. The test stand PAC also communicates using a proprietary protocol directly with the plant master programmable logic controller (PLC).

The vibration system measures two three-axis accelerometers for each test station and produces 1/3 octave band and RMS average dB velocity readings. The control system compares the spectrum data to permissible limits for the particular UUT model, generates pass/fail flags, displays, prints and stores results.

5. TEST OPERATION

5.1 Test profile setup
For each UUT model tested, the PAC stores test configuration (profile) data for three types of test. The “functional” test demonstrates within a short period of time that the UUT meets all production specifications. The “performance” test requires longer time but obtains tighter control of test conditions for performance evaluation. The “manual” test mode allows an engineer to perform a test of any duration and interact with the test as it proceeds. All test types include starting and stopping the UUT, data recording at three steady-state load points, and, for some UUTs, an oil shuttle control valve test.

The test engineer may edit test profiles offline, using a spreadsheet function. Each profile contains as many as 250 parameters, including such configurable items as UUT description, pressure and temperature setpoints, initial control valve settings, speed settings, desuperheater operation schedule, oil cooling setup, stability dwell times and limits, performance target values and pass/fail tolerances. Although each UUT model may be configured uniquely, in practice there are UUT families that share many settings.

Refrigerant properties used for performance calculations in the test profile and test reports link from the NIST REFPROP™ refrigerant properties database. Any set of current or historical properties may be selected.
5.2 Variable frequency drive (VFD) setup
Another offline setup task is to configure VFD parameters. The VFD accommodates any type of compressor motor, including conventional induction motors as well as surface or interior type permanent magnet motors. However, the drive must be configured (or “tuned”) for each particular motor using a table of approximately 100 parameter settings. The appropriate settings must be determined by analysis or experiment, and then added to a spreadsheet database in PC #1. As a test begins, the PAC triggers the PC, and the PC uploads the appropriate parameters to the drive, reads them back for verification and resets the drive.

5.3 Test sequence
The operator mounts and connects the UUT and then the PAC executes the test automatically, as follows:

- Operator – Place UUT onto test table mounting adapter. Connect suction and discharge piping (adapters use o-ring sealed V-band clamp joints, for quick fit-up). Attach electrical terminal box. Install vibration probes. Wand UUT barcodes; start vacuum purge; insert interlock key into terminal box.
- PAC – Run vacuum purge cycle. When purge completes, charge test station with refrigerant.
- Operator -- Connect oil supply hoses
- PAC -- Perform test:
  - Upload drive parameters, inject oil, set test profile, position control valves
  - Start the UUT drive. For fixed speed UUTs, set unload displacement and accelerate the uut to running speed. For variable speed UUTs, accelerate the UUT to unload speed. Then start liquid injection and suction temperature control.
  - When intermediate pressure recovers, enable suction and discharge pressure control, ramp up discharge pressure setpoint
  - Set part load displacement or accelerate the UUT to part load speed, continue to ramp up discharge pressure
  - Set full load displacement or accelerate the UUT to full load speed, continue to ramp up discharge pressure to target setpoint
  - Dwell at full load until all performance parameters have stabilized within prescribed tolerances for the prescribed time; record data over a prescribed interval (usually one minute or three minutes)
  - For certain UUTs, perform a shuttle control valve test, as follows: ramp discharge pressure to reduced setting, observe change in oil flow rate to detect shuttle valve movement, ramp discharge pressure back to original setting, verify oil flow rate returns to normal
  - Set part load displacement or decelerate the UUT to part load speed; dwell for stabilization; take data
  - Set unload displacement or decelerate the UUT to unload speed; dwell for stabilization; take data
  - Stop liquid injection. When suction piping reaches room temperature, stop the UUT drive. Test stand suction and discharge pressures equalize. Save test data. Prompt the operator to remove the interlock key and disconnect oil hoses, or repeat the test. Subsequent interlock key transfer to the other station permits the other station to charge and run a test.
- PAC – Run the refrigerant reclaim cycle. When reclaim completes, vent the test station to ambient pressure; lockout the test station in “safe” mode; print and save the test data report.

5.4 Test report
A 3-page test report is available after the test. Page 1 lists UUT identification data, test summary status, test conditions and measured performance for each load point. It also shows vibration graphs and a radar plot that illustrates test parameters in or out of tolerance. Page 2 lists all vibration 1/3 octave measurements with pass/fail notation as well as amplitude/frequency charts. Page 3 is a diagnostic report, used for troubleshooting and maintenance.
6. RESULTS

- The test stand shows excellent data correlation with UUTs tested in other laboratories and excellent data repeatability from station to station, test to test and day to day.
- Functional tests, as described above with three steady data points and one pressure excursion test, generally complete within 16-20 minutes, with ±3.5kPa pressure stability and ±1.1°C superheat stability over a one-minute period, for each data point.
- With stability tolerances relaxed somewhat, the largest UUT completes a functional test within 12-14 minutes. Tests for smaller UUTs can run more quickly.
- A large UUT completes a performance test in about 45 minutes, with ±1.7kPa suction pressure stability, ±3.5kPa discharge pressure stability and ±0.28°C superheat stability over a three-minute period.

REFERENCES


NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures Database (REFPROP), NIST Standard Reference Database 23, Version 9.1, National Institute of Standards and Technology, Gaithersburg, MD