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ABSTRACT

The goal of the paper is to present software providing computer-aided analysis of results obtained from calorimetric testing. References on calorimetric testing facilities have been reviewed. A calorimetric test facility developed, designed, and built in-house has been presented. The software providing computer-aided analysis of test results obtained from the calorimetric testing as an integral part of the facility has been discussed. Conclusions have been given.

INTRODUCTION

As per ASHRAE Handbook (ASHRAE 1998) environmental test facilities are used to simulate an environment or combination of environments under laboratory controlled conditions that duplicate or exaggerate the effects found in actual service. They assist the engineer and scientist in exploring the effect of equipment and in developing equipment for resistance to many environmental forces. The handbook classifies the calorimetric test facilities as climatic temperature chambers for temperature soaks at low and high extremes. There are available standards ANSI/ASHRAE 16-1988 (ASHRAE 1988), ANSI/ASHRAE 37-1988 (ASHRAE 1988), ANSI/ASHRAE 111-1988 (ASHRAE 1988), and ANSI/ASHRAE 116-1995 (ASHRAE 1995) related to the calorimetric testing. Standard ASHRAE 16 divides the calorimeters in two groups: calibrated or balanced. The first group requires calibration of heat and humidity infiltration. The second group has a surrounding compartment with dry bulb temperature equal to a temperature in the surrounded room. Standard ASHRAE 37 recommends four test arrangements of the calorimetric test facilities realizing: the tunnel air-enthalpy method, the loop air enthalpy method, the calorimeter air enthalpy method, and the room air enthalpy method. Standard ASHRAE 111 covers measurement, testing, and balancing techniques. Standard ASHRAE 116 relates to rating of seasonal efficiency of air conditioning and heat pumping systems.

A calorimetric testing facility consisting of two environmentally controlled rooms simulating indoor and outdoor conditions is available at ACRC of the University of Illinois at Urbana Champaign Yin et al. (2000). The walls of each room are constructed of 30cm thick polyurethane. A variable speed wind tunnel in each chamber simulates the range of operating conditions encountered in real applications. Simultaneous operation of a glycol chiller and a condenser of a unit under test balances the outdoor temperature. Simultaneous operation of a heater and a humidifier located in the indoor room and an evaporator of the unit under test, balances the indoor temperature and humidity. Three independent methods are used to determine capacities in each room: calorimeter balance, airside enthalpy balance, and refrigerant side balance. The measurement system meets the requirements of standards ASHRAE 37 and ASHRAE 116. During the test, the most important parameters are monitored in real time by a data acquisition system, then the raw data are transferred to an Excel file, and sets of data points, each of which is averaged within a 10-minute interval, is treated by an EES program (Klein and Alvarado, 1995). Similar calorimetric test facilities, consisting of two environmentally controlled test chambers and simulating indoor and outdoor conditions with precise control of the air dry bulb and wet bulb temperatures is located at the Thermal Technology Center of the National Research Council Canada (Linton et. al. 1994), at Herrick Laboratories at Purdue University (Li et al. 2000), and at SINTEF Energy Research at Trondheim, Norway (Hafner 2000). Thermo-King Corporation’s calorimetric test facility (Kwon 1998) complies with ARI Standard 1110-2001 (ARI 2001). The above systems are intended for testing and rating systems and system components. Also, there are available many various calorimetric facilities for testing separate system components (condenser, evaporators, and compressors). Such testing facilities are described by Hagan et al. (1993), Pearson (1995), Horton and Groll (1998), Preissner et al. (1998), and Litch and Hrnjak (2000).

The review of publications on calorimetric testing facilities shows that there are various designs, which depend on the nature of the required testing and features of the objects to be tested. The MCC calorimetric testing facility is oriented for mobile HVAC products manufactured at MCC and the facility's concept is a calibrated temperature chamber to provide testing and rating of split and single package mobile HVAC systems at different indoor and outdoor conditions and testing and rating of refrigeration components at different operating conditions. For heating systems, the range of the outdoor conditions is extended to ultra-low temperatures.

Each qualification test is intended to verify compliance of operating (actual) performance characteristics and performance characteristics calculated during functional design. Successful completion of this task requires, first of all, correct and sufficient measurements. However, the results obtained during the test are just a set of data. In order to turn them into information confirming correctness of measurements and compliance of the performance characteristics some calculations are required. The more extensive the calculations are, the more information from the completed test will be obtained. Therefore, software providing computer-aided analysis of test results obtained from the calorimetric testing is an integral part of the calorimetric testing facility. The goal of the paper is to present the software providing computer-aided analysis of results obtained from calorimetric testing at the MCC testing facility, which outputs comprehensive information about the test and system under test.

MCC CALORIMETRIC TESTING FACILITY

The MCC calorimetric testing facility (Figure 1) consists of two environmentally controlled rooms made of 10" expanded polystyrene panels. One room, which has a volume of 2326 ft^3, is intended to simulate indoor temperature and humidity conditions and is called the Indoor Room. Another room, which has a volume of 1833 ft^3, is intended to simulate outdoor conditions, and is called the Outdoor Room. There is an intermediate door between the Indoor and Outdoor Rooms to enable testing of single package HVAC systems. The facility is equipped with a cascade refrigerating system, a heating and humidifying system, and an ethylene glycol system. Operation of the entire facility is controlled by a SCADA (supervisory control and data acquisition) system.

Figure 1: MCC Calorimetric Testing Facility

The Indoor Room has the heating and humidifying system, that consists of a duct with a fan, an electrical heater, a steam distributor of a humidifier, and humidity absorption area. The humidifier itself is located outside the Indoor Room. An evaporator of a split AC system under test is placed inside the Indoor Room. Simultaneous operation of the heater, humidifier, and evaporator provides the stable indoor temperature and humidity conditions. The indoor temperature is controlled by an SCR control element, and the indoor humidity control is provided by P+I on/off cycling. The Outdoor Room consists of a two-section duct, each section of which has a fan and a cooling coil covering both sections at the fans' discharge side. The coil is piped to the refrigeration system located outside the Outdoor Room in a Refrigeration Equipment Room. A condenser of the split AC system under test or a heating coil of a heating system under test is placed inside the Outdoor Room. Simultaneous operation of the condenser or of the heating coil and the refrigeration system of the calorimetric test facility provides the stabilized outdoor temperature conditions.

The cascade refrigeration system consists of three closed loops: R22, R23 and SYLTHERM XLT (Figure 2). A similar cascade refrigeration system is discussed in paper by Lynde and Yonkers (1996).

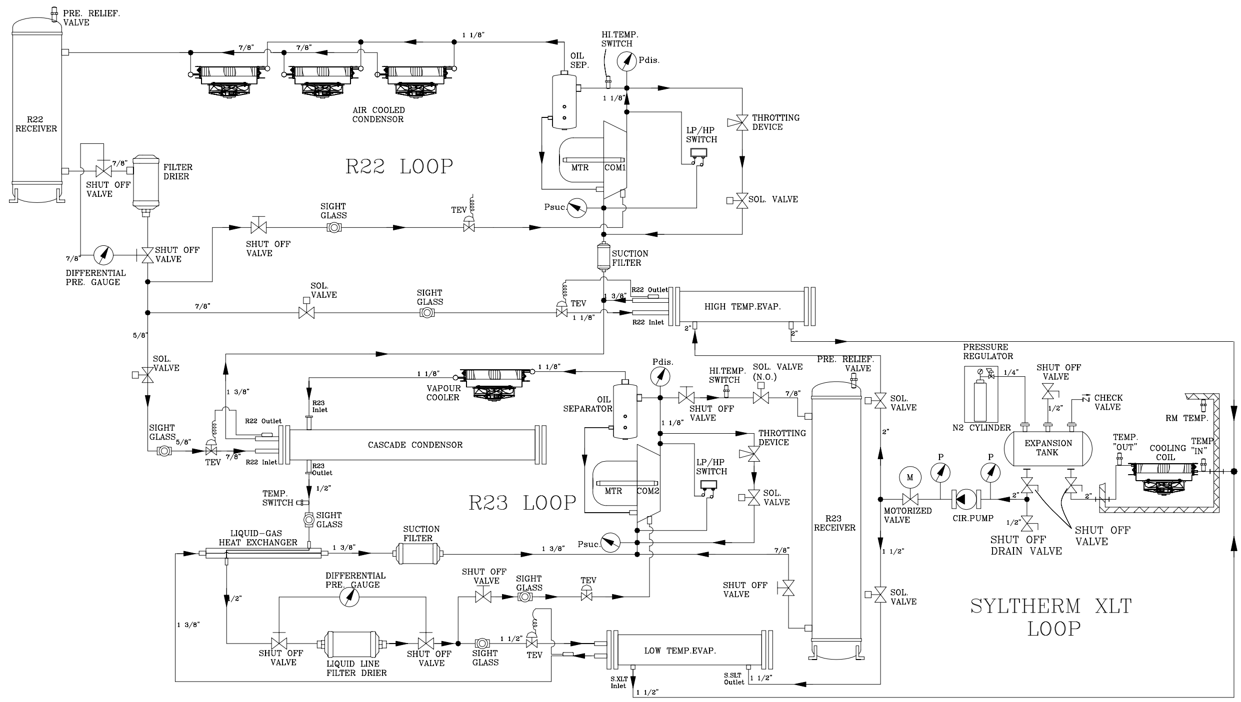

Figure 2: Cascade Refrigeration System

The R22 loop consists of a semi-hermetic compressor with liquid injection cooling, an oil separator, a condenser unit, a receiver, a filter-drier isolated with two shut-off valves, two parallel circuits, a suction filter, and related piping. One circuit consists of a solenoid valve, an expansion valve, and the tube side of a shell-in-tube heat exchanger, which is a high temperature evaporator. Another circuit consists of a solenoid valve, an expansion device, and the tube side of a shell-in-tube heat exchanger, which is a cascade condenser. The condenser unit consists of three parallel sections with each section consisting of a fan and a condenser coil. There is a bypass line with a solenoid valve and a throttling device connecting the compressor discharge side and suction side to provide reduced capacity.

The R23 loop consists of a semi-hermetic compressor with liquid injection cooling, a vapor cooler incorporated into the middle section of the condenser unit, the shell side of the cascade condenser, a liquid-gas heat exchanger, a filter-drier isolated with two shut-off valves, an expansion valve, the tube side of a shell-in-tube heat exchanger, which is a low temperature evaporator, a suction filter, and related piping. A vapor receiver is connected to the compressor in parallel and has a normally opened solenoid valve on a pipe between the receiver and the compressor discharge side. When the R23 loop is on, the valve is closed and gaseous R23 is pumped from the receiver to the system. When the R23 loop is off, the valve is opened, all R23 liquid is turned to the gaseous state, and occupies the entire R23 loop volume including the receiver volume. Thus, an acceptable standing pressure in the R23 loop is maintained. There is a bypass line connecting the compressor discharge side and suction side with a solenoid valve and a throttling device to provide reduced capacity.

The SYLTHEM XLT loop consists of the cooling coil installed in the Outdoor Room, an expansion tank, a pump, a motorized valve regulating SYLTHERM XLT flow rate, two parallel circuits, and related piping. One circuit has a solenoid valve and shell side of the high temperature evaporator. Another circuit has a solenoid valve and shell side of the low temperature evaporator. All components are rated for the operation at ultra-low temperatures; most of the components are made of stainless steel. Threaded copper to stainless steel joints are avoided. A nitrogen blanket inside the expansion tank protects the SYLTHERM XLT from contact with humid air. The nitrogen loop consists of a nitrogen cylinder, pressure regulator, the expansion tank, and a check valve. The check valve provides bleeding of nitrogen to maintain a pressure blanket.

The refrigeration system operates in two modes: high temperature mode and low temperature mode. In the high temperature mode the R22 loop cools the SYLTHERM XLT in the high temperature evaporator. In the low temperature mode the R22 loop cools the R23 in the cascade condenser, the R23 loop cools the SYLTHERM XLT in the low temperature evaporator. In both cases the SYLTHERM XLT is pumped to the cooling coil to provide cooling action in the Outdoor Room. The solenoid valves are switched on and off accordingly. During high temperature mode operation, capacity control is provided by the engagement and disengagement of the R22 bypass line and R22 compressor, depending on air temperature in the Outdoor Room. During the low temperature mode the R22 bypass line and compressor are engaged and disengaged depending on R23 liquid refrigerant temperature at the cascade condenser outlet. The R23 bypass line and compressor are engaged and disengaged depending on air temperature in the Outdoor Room. The SYLTHERM XLT pump operates continuously during all modes of operation.

The ethylene glycol system feeds the heating coils of the heating system under test with a heated ethylene glycol water mixture. The ethylene glycol system consists of an electrical heater, which also operates as an expansion tank, a pump, and related piping. Temperature control is provided by on/off cycling of the electrical heater.

The SCADA system controls the operation of the entire calorimetric test facility and records in real time all operating parameters of units under tests. The SCADA system includes: a computer located in the Control Room, a PCI data acquisition card (16 bit resolution, ±10V range), a data acquisition chassis accepting up to 12 modules, three RTD input modules with 4 channels per module, two thermocouple input modules with capacity of 32 thermocouples per module, two analog 0-5V/4-20mA modules having 32 channels per module, a digital input module with 32 channels, two digital output modules each having 16 channels, and a 4-channel analog 4-20mA output module. The data acquisition software (LABVIEW®), is part of the data acquisition system and runs the data acquisition process and numerically and graphically outputs the acquired data.

The test facility is intended for testing in accordance with standards ASHRAE 16 and ASHRAE 37 utilizing the tunnel air enthalpy method. System capacity is determined by at least two methods, which are: calorimeter balance and refrigerant balance. If testing is conducted in accordance with the standard ASHRAE 37, the third method of the determination of cooling capacity, which is the air side balance, is applied. An integral and significant part of the MCC calorimetric testing facility is the developed in-house software providing computer-aided analysis of test results, which outputs validated performance characteristics and their uncertainties for each test.

INSTRUMENTATION AND UNCERTAINTY ANALYSIS

During each test the following basic parameters related to a system under test and the system components are measured: outdoor air temperature (which is at the condenser unit inlet), indoor air temperature and relative humidity (which is at the evaporator unit inlet), refrigerant pressure and temperature to the compressor inlet (suction) and compressor outlet (discharge), refrigerant pressure and temperature to the condenser coil inlet and outlet, air temperature at the condenser outlet, refrigerant pressure and temperature at the expansion valve inlet, refrigerant pressure and temperature at the evaporator coil outlet, air and relative humidity at the evaporator outlet, liquid refrigerant flow rate, power consumed by the compressor, condenser fans and evaporator blowers, condensate collection, time, power input to the Indoor Room, and power input to the Outdoor Room. Also, SYLTHERM XLT flow rate and temperatures at the inlet to and outlet from the Outdoor Room are measured. If the system under test has a number of coils, refrigerant pressures and temperatures at the inlets and outlets to each coil are measured. Also, temperatures at the outlet of each circuit of a coil, mostly for evaporator coils, may be measured. If standard ASHRAE 37 is applied, air static pressures and air flow rates through the evaporator and/or condenser coils are validated. When tests are completed condensate collection and/or miscible oil concentration in liquid refrigerant pipe are weighed.

The uncertainty of the measurements carried out includes total sensor uncertainty, total data acquisition uncertainty, and errors associated with lead lengths. Ambient temperatures are monitored using precision 100Ω platinum RTD's. Calibrations confirm accuracies of ±0.02°C in the range of -40°C to 60°C. Surface pipe temperatures are monitored using T-type thermocouples with enhanced standard thermocouple accuracies (± 0.5°C for T-type SLE). Humidity is monitored using capacitive-film sensors. These transducers have integrated signal conditioning, temperature compensation, and a 4-20mA analog output signal. The stated accuracy of these sensors is ±1%RDG in the range of 10%RH to 90%RH. Power measurements are carried out via precision wattmeters with stated accuracies of

±0.5%FS. Pressure transducers coupled to the units under test are the bonded stain gauge type. These transducers have integrated signal conditioning, temperature compensation, and a 4-20mA analog output signal. The calibrated accuracies of these sensors is ±1%RDG. The refrigerant flow rate of units under test is monitored using a Coriolis mass flow meter. The calibrated accuracy of this sensor is stated at ±0.15%RDG in the range of 0-47lbs/min. Static duct air pressures are measured using differential pressure transducers. These transducers have integrated signal conditioning, temperature compensation, and a 4-20mA analog output signal. The stated accuracy of these sensors is ±0.25%FS in the range of 0-4 inches of water column. All calibrations are traceable to NIST.

Uncertainty analysis of validated performance characteristics complies with Taylor 1994 and ASHRAE Guideline 2-1986. Since heat input within τ , *sec* period of time is an integrated value, average integrated values and standard deviations of each measured and validated parameter are determined as:

$$\bar{x} = \frac{1}{\tau} \cdot \int_0^\tau x(t) \cdot dt \, , \tag{1}$$

$$\sigma = \sqrt{\frac{1}{\tau} \cdot \int_0^\tau [x - x(t)]^2 \cdot dt} \, . \tag{2}$$

where $x(t)$ - is a value of a parameter at a certain moment t in which measurements are accomplished.

The basic performance characteristics of main components are: the condenser capacity, the evaporator capacities, and the compressor volumetric and isentropic efficiencies. Uncertainties of their performance characteristics are in Table 1.

Parameter	Uncertainty
Condenser and Evaporator Capacity Q	$\frac{\Delta Q}{\overline{Q}} = \frac{\Delta G}{\overline{G}} + \frac{\Delta h_{in} + \Delta h_{out}}{\overline{q}}$; $\Delta h = \sqrt{\Delta h_T^2 + \Delta h_p^2}$; $\Delta h_T = (\partial h / \partial T)_p \cdot \Delta T$; $\Delta h_P = (\partial h / \partial p)_T \cdot \Delta p$
Volumetric Efficiency η_v	$\frac{\Delta \eta_v}{\eta_v} = \frac{\Delta G}{\overline{G}} + \frac{\Delta \rho''}{\overline{\rho''}}$; $\Delta \rho'' = \sqrt{\Delta(\rho'')_T^2 + \Delta(\rho'')_p^2}$; $\Delta \rho''_T = (\partial \rho'' / \partial T)_p \cdot \Delta T$; $\Delta \rho''_P = (\partial \rho'' / \partial p)_T \cdot \Delta p$
Isentropic Efficiency η_s	$\frac{\Delta \eta_s}{\eta_s} = \frac{\Delta P}{\overline{P}} + \frac{\Delta G}{\overline{G}} + \frac{\Delta h_{in} + \Delta h_{out}^s}{\overline{w_s}}$

Table 1: Uncertainties of Performance Characteristics

The following designations are in Table 1: ΔG - is uncertainty of measured mass flow rate G ; Δh - is uncertainty of enthalpy at the inlet (subscript “in”) to or at the outlet (subscript “out”) from the condenser or evaporator associated with uncertainty of pressure p and temperature T ; Δh_T - is uncertainty of enthalpy associated with uncertainty of temperature T ; Δh_p - is uncertainty of enthalpy associated with uncertainty of pressure p ; q - is specific condenser or cooling capacity, which is a positive difference between outlet and inlet enthalpies; $\Delta \rho''$ - is uncertainty of density ρ'' of vapor refrigerant associated with uncertainty of pressure p and temperature T ; $\Delta \rho''_T$ -

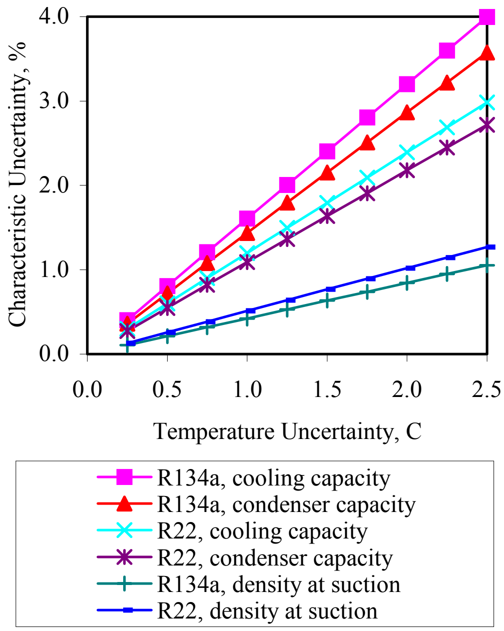

Figure 3: Impact of Temperature Uncertainty

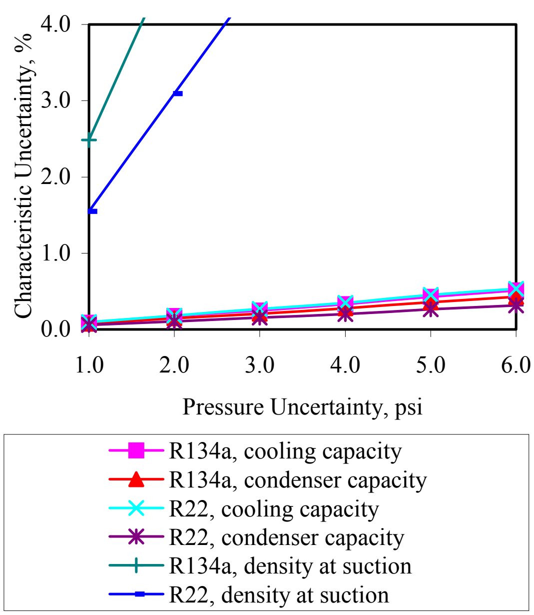

Figure 4: Impact of Pressure Uncertainty

is uncertainty of density ρ'' of vapor refrigerant associated with uncertainty of temperature T; $\Delta\rho''_p$ - is uncertainty of density ρ'' of vapor refrigerant associated with uncertainty of measured pressure p; $\Delta\eta_v$ - is uncertainty of volumetric efficiency η_v; $\Delta\eta_s$ - is uncertainty of isentropic efficiency η_s; ΔP - is uncertainty of measured compressor power P; w_s - is specific compressor work, which is the difference between outlet and inlet enthalpies; Δh^s_{out} - is uncertainty of compressor work w_s at discharge side, which is equal to uncertainty of enthalpy of vapor compressed from the actual suction state to the discharge pressure at the constant entropy.

Pressure and temperature uncertainties have strong effects on the uncertainties of the basic performance characteristics of the system components. Figure 3 and Figure 4 show calculated uncertainties of cooling capacities, condenser capacities, and compressor volumetric and isentropic efficiencies. All calculations are done at a condensing temperature of 40°C, evaporating temperature of 0°C, sub-cooling of 5°C, and superheat of 5°C for refrigerants R134a and R22. Uncertainty of evaporator capacity is influenced by temperature uncertainties to a greater extent. Condenser capacity is influenced by temperature uncertainties to a lesser extent. Refrigerant density at the compressor suction and the compressor performance characteristics are influenced by temperature uncertainties even less than the condenser capacity. Pressure uncertainties seriously impact density of refrigerant at the compressor suction. Since compressor volumetric and isentropic efficiencies depend on refrigerant density at the compressor suction, use of precise pressure transducers is required. The impact of pressure uncertainties on condenser and evaporator capacity is not significant. Impact of temperature and pressure uncertainties on uncertainties of R22 performance characteristics is higher than the impact on uncertainties of R134a performance characteristics, which means that different refrigerants provide different uncertainties of performance characteristics.

SOFTWARE FOR COMPUTER AIDED ANALYSIS OF TEST RESULTS

When each test is completed, the data recorded by the LABVIEW® software are converted to ASCII code. The converted data form an input file for the software providing computer-aided analysis. All calculations are done for each moment when measurements are taken, and integrated over the entire test period as per formulas (1) – (2). Time between each successive measurement is 1.2 seconds, approximately. The period of each test is about one hour. The software outputs the following: general information, measurement configuration file content, statistical analysis of all measured data, analysis of compatibility of all measured refrigerant pressures and temperatures, performance characteristics of evaporator, performance characteristics of compressor, performance characteristics of condenser, performance characteristics of condenser fans, performance characteristics of evaporator blowers, pressure drops and temperature changes in piping, performance characteristics of the complete system, and uncertainty analysis. Also, the software has an interface with software providing functional design of air conditioning and heat pumping systems and system components, which validates and outputs discrepancies between the calculated and test results.

The general information output includes: input file specification, measurement configuration file specification, output file specification, duration of the test, specifications of system components (refrigerant, condenser coil, evaporator coil, compressor, condenser fan(s), evaporator blower(s), and piping schematics).

The measurement configuration file consists of associations of all physical parameters (temperatures, pressures, flow rates, wattmeter readings, etc.) in the software for computer aided analysis of test results with channels of the data acquisition system, uncertainties of each measuring instrument, and control values for level of acceptable fluctuations of main parameters. Normally, the main parameters representing system stabilization are: indoor temperature and humidity, outdoor temperature, refrigerant flow rate, discharge and suction pressures, and suction temperature.

The statistical analysis provides histograms, average integrated values, maximal and minimal values, lower bound in one, two, and three standard deviations of the main parameters. The statistical analysis of all remaining measured parameters includes average integrated values, minimal, and maximal values, and lower bounds in one, two, and three standard deviations. According to ASHRAE guideline (ASHRAE, 1996) for normal distribution, the standard deviation has the following meanings: 68.3% of the data will be within $\pm\sigma$; 95.5% of the data will be within $\pm 2\sigma$; and 99.7% of the data will be within $\pm 3\sigma$.

There are two sides of a success or a failure of the completed testing. One side relates to the equipment and measuring system of the calorimetric testing facility, and the other side relates to the system under test. Statistical analysis, compatibility of measured pressures and temperatures, and discrepancies between methods validating evaporator capacity – are the three points determining the success or failure of the completed test related to the testing facility. Compliance of specified or calculated performance characteristics with the performance characteristics obtained from test data relates to the success or failure of the system under test.

Evaporator capacity and refrigerant mass flow rate are validated by two methods if standard ASHRAE 16-1988 is applied and three methods if standard ASHRAE 37-1988 is applied. Non-compliance between methods validating evaporator capacity has two sides as well. One side relates to the measuring system. The other side is associated with the unit under test. For example, if the thermal balance of the Indoor Room shows higher evaporator capacity than the mass flow meter, there is the probability of liquid flowing from the evaporator to the suction pipe. In this case the thermal expansion valve of the system under test should be adjusted for a higher superheat and the test should be repeated. If the thermal balance of the Indoor Room shows lower evaporator capacity than the mass flow meter, there is the probability of excessive oil carry over. In order to verify oil carry over in systems with miscible oils, it is sufficient to take a refrigerant sample from the liquid line. For systems utilizing compressors with high oil carry over it is recommended to have a loop with a shut off valve, an oversized coalescing oil separator, oil flow meter or oil level meter, and another shut off valve, which enables an option to validate oil carrier over the compressor and to investigate the influence of oil charge on the performance characteristics of systems under test.

Performance characteristics of the evaporator under test (evaporator capacity and superheat at the evaporator outlet) are associated with indoor temperature and relative humidity, air flow rate, liquid refrigerant temperature at the inlet to the expansion valve, evaporating pressure and temperature of refrigerant, and refrigerant mass flow rate. Performance characteristics of the condenser under test (condenser capacity and subcooling) are determined at outdoor temperature, air flow rate, condensing pressure and temperature of refrigerant, refrigerant temperature at the condenser inlet, and refrigerant mass flow rate. Performance characteristics of the compressor under test (refrigerant mass flow rate, volume flow rate, compressor power, potential cooling capacity, volumetric efficiency, isentropic efficiency, and discharge temperature) are determined at the compressor speed, suction and discharge pressures and suction temperature. Performance characteristics of the entire system under test (cooling capacity, which is lower than the evaporator capacity, total power consumption, and COP) are associated with indoor and outdoor conditions.

CONCLUSIONS

The MCC calorimetric testing facility's concept is a calibrated temperature chamber to provide testing and rating of split and single package mobile HVAC systems at different indoor and outdoor conditions and testing and rating of refrigeration components at different operating conditions. Software providing computer aided analysis is an integral part of the calorimetric testing facility. The software utilizes recorded operating parameters obtained during testing of units under test as input data and provides statistical analysis of all measured data including histograms of the control parameters, analysis of compatibility of all measured refrigerant pressures and temperatures, performance characteristics of evaporator, performance characteristics of compressor, performance characteristics of condenser, performance characteristics of condenser fans, performance characteristics of evaporator blowers, pressure drops and temperature changes in piping, performance characteristics of complete system under test, and uncertainty analysis. Also, the software has an interface with software providing functional design of air conditioning and heat pumping systems and system components to validate discrepancies between calculated (designed) performance characteristics and actual (experimental) results.

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