Testing methods applicable to refrigeration components and systems

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1. INTRODUCTION

Evaluating the functional performances of any component or system is answering two series of questions:

- How much is it satisfying the requirements? What else is it offering? Which other advantage? Etc.
- What is the energy consumption level? What are the maintenance requirements? How much environmental impact? Etc.

The test of the components or of the system considered must include enough measurements to answer these questions.

This usually requires defining some mass and energy flow rates, associated to temperature and pressure potentials. For example, defining the functional performance of a heat exchanger (condenser, evaporator…) is answering to the following questions: how much heat is it transferring for a given temperature difference, or vice versa, and how much "auxiliary" (fan or pump) energy consumption does it generate? For a compressor, the question is: how much fluid (or how much heat) is transferred for which pressure ratio, or vice-versa, and how much energy is consumed?

This paper presents an overview of various testing methods and measuring techniques, including the definition of enthalpy flow rates, identification of ambient losses in a calorimeter and global energy balances.

Examples of testing methods and experimental results are presented, first on refrigeration components (compressor, evaporator, condenser) and then on a whole refrigeration system (room air conditioner).

2. TESTING OF A COMPRESSOR

2.1 Test bench description

The example presented hereafter concerns the test of a hermetic scroll compressor, supplied with refrigerant R134a and polyolester oil. In this kind of compressor, the refrigerant circulates first through the electrical motor, to cool it; and then enters into the compression chamber [1].

A small lubrication pump is mounted on the crankshaft in the bottom of the compressor shell, which circulates the oil to the bearings and scrolls through an orifice located inside the crankshaft. This compressor is confronted to two problems: the motor cooling (due to the high evaporation temperature), and the scroll lubrication: when the compressor turns slowly, the pumping effect decreases and the compressor is poorly lubricated. Under these conditions, the compressor internal leakage could also become more important.

The compressor is supplied with a pulse-width modulated (PWM) inverter, which is used to regulate the compressor supply frequency and thus its speed. The inverter is used in the mode V/F control for constant torque loads and at a carrier frequency of 15 kHz. The compressor and the inverter are installed inside two separated calorimeters to determine their ambient losses as shown in Figure 1.

Each calorimeter works at a constant air temperature by manually tuning the fan coil water flow rate, which is used to compensate the heating contributions of the lamps and the component to be tested (the inverter or the compressor).
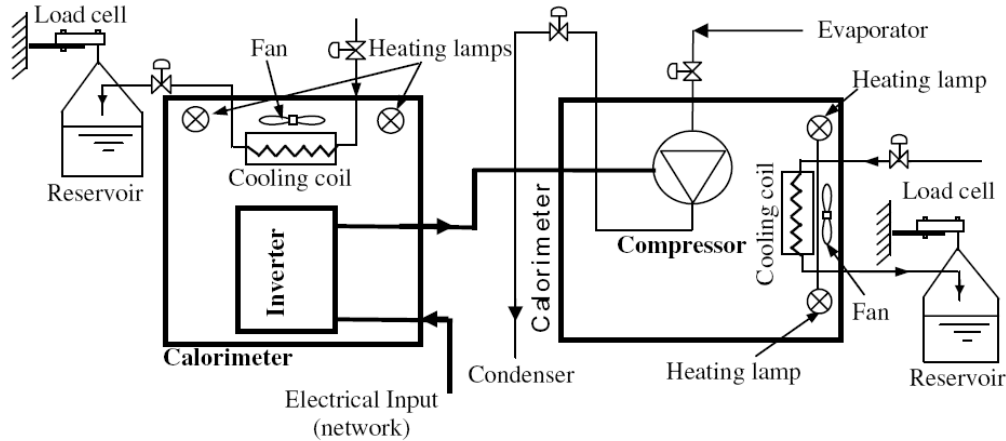

Figure 1 Schematic view of the test bench

For the inverter, the calorimetric thermal balance is preferred to any measurement of output power, because of the electrical disturbances created by the inverter itself that exclude the use of conventional power transducers. The total conductances of the compressor and inverter calorimeters are estimated by calibration.

The following measurements are carried out: compressor speed, inverter power, compressor supply and exhaust pressures and temperatures, compressor surface temperature. In both calorimeters, the air temperatures and the water flow rates are also measured.

Two sources of uncertainty are considered for the temperatures: one coming from the thermocouple tolerance (±0.5 K) and the other one coming from the data acquisition system (±0.3 K). Thus, an overall absolute uncertainty of ±0.6 K (relative uncertainty is smaller) is obtained.

The refrigerant mass flow rate is determined from the evaporator steady-state thermal balance, with an uncertainty estimated, by comparison with a Coriolis flow meter, to ±3%.

The compressor power is measured with a power transducer, only for the tests where it is supplied directly from the network at 50 Hz. In the other cases the inverter supply power is measured.

As in this test bench the compressor works at variable speed, its frequency is measured directly in the inverter control system. According to the inverter manufacturer, this frequency is given with an accuracy of ±0.01%.

Inverter and compressor calorimeter load cells, used to measure water flow rates by weight, were calibrated to reduce their uncertainties. In the tested range, the compressor calorimeter load cell has an uncertainty of ±0.4% and the inverter calorimeter load cell ±0.1%. By using the uncertainty propagation method an uncertainty for the compressor and the inverter calorimeter water flow rates of ±2.5% and ±1.5% are obtained, respectively.

2.2 Test results

Examples of results are presented in Figure 2: the volumetric and isentropic effectiveness are plotted as functions of the supply pressure and of the pressure ratio imposed to the compressor. Isentropic effectiveness shows a maximum for a pressure ratio comprised between 2 and 3, corresponding to internal built-in volume ratio. A linear relation between compressor electrical consumption and exhaust pressure is also stated [2].
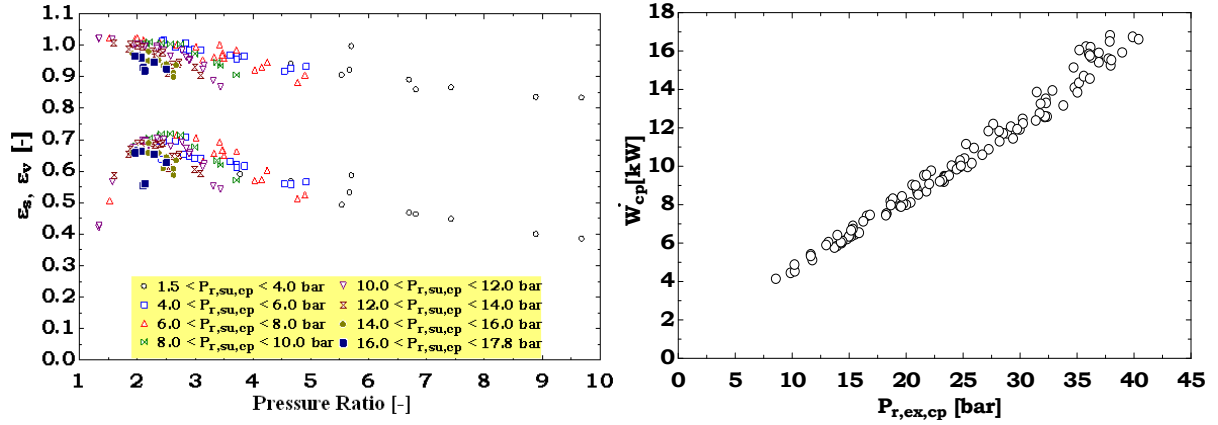
Figure 2 Test results on the compressor

3. TESTING OF AIR-TO-REFRIGERANT HEAT EXCHANGERS

The target of these tests is to determine the performances of an air-heated evaporator and of an air-cooled condenser. The evaporator and the condenser are here tested separately, in order to have an easier control for running conditions [5].
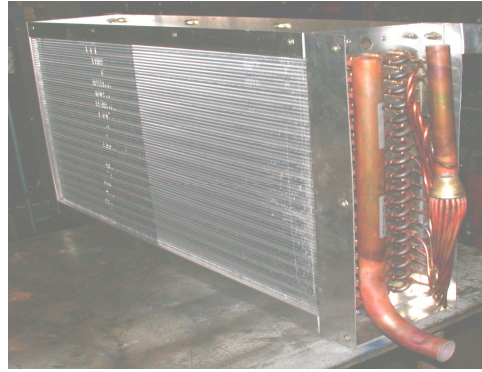

Figure 3 View of the evaporator

3.1 Description of the test bench

The evaporator and condenser are installed in an air network with controlled temperature and relative humidity. Figure 4 shows the general scheme of the test bench, which includes the refrigerant, water and air circuits. The positions of all temperature and pressure sensors are also indicated.

3.1.1 The air side network

The air is blown in open loop with a two-speed fan, which is located at the supply of the air network. The air mass flow rate is adjusted by tuning the speed of the fan or the position of a damper located at the inlet of the box. A set of electrical heating resistances is used to bring the ambient air to the required temperature, with the help of PID controller.

For horizontal condenser tests, a 4-hole orifice plate, located in the middle of the box, is used to measure the airflow rate. Air flows into the vertical branch only (the horizontal branch is thus fully closed).

For evaporator tests, water vapor injection is used to control the proper air humidity at the supply of the evaporator. A standard nozzle (ISO 5167-1980) is located behind evaporator in order to measure the air flow rate [3]. The vertical branch of the air network is then fully closed.
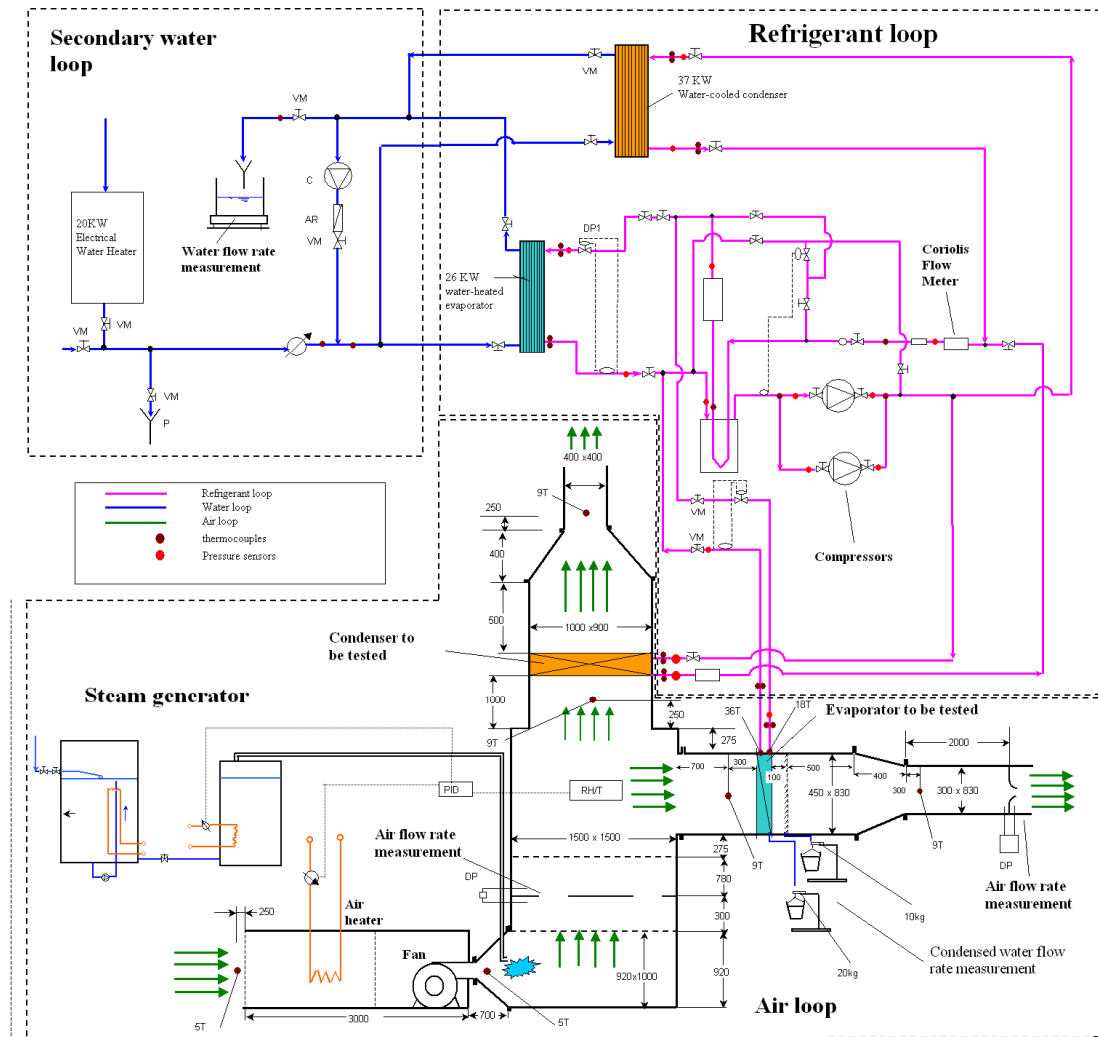
Secondary water loop

Refrigerant loop

VM

37 KW
Water-cooled condenser

20KW
Electrical
Water Heater

Water flow rate
measurement

C

AR
VM

DP1

Coriolis
Flow
Meter

26 KW
water-heated
evaporator

VM VM

VM
P

Refrigerant loop
Water loop
Air loop
thermocouples
Pressure sensors

Compressors

400 x400
9T
250
400
500
1000 x900
1000

Condenser to
be tested

Steam generator

Evaporator to be tested

36T 18T
9T
250
275
2000

PID

RH/T

Air flow rate
measurement

1500 x 1500

DP

250
Air
heater

Fan

5T

3000

700

5T

700
300
100
500
450 x 830 400 300
300 x 830
9T
275
780
300
920

9T

10kg

20kg

DP

Air flow rate
measurement

Condensed water flow
rate measurement

920x1000

Air loop

Figure 4 Schematic view of the test bench

3.1.2 Refrigerant network

The *evaporator* to be tested is connected to a refrigerant network with variable speed scroll compressor, water-cooled condenser, receiver and Coriolis flow meter. The water flow rate of the condenser is adjusted to control the proper condensing pressure at the refrigerant side.

Almost the same refrigerant network is used to test the *condenser*, except that the latter is replacing the water-cooled condenser, and that a water-heated evaporator replaces the evaporator previously tested.

An internal heat exchanger is installed between the high-pressure liquid line at the condenser exhaust and the low-pressure vapor line at the evaporator exhaust. This reduces the risks of a two-phase state entering the Coriolis flow meter and/or liquid entering the compressor.

3.1.3 Water network

Open loop water networks are used here for both the water-cooled condenser and the water-heated evaporator.

The hot water supplied to the water-heated evaporator is coming from a gas boiler. The supply water temperature is around 30~35°C.

The condenser is supplied with tap water, whose temperature is around 10 to 12 °C.

Each water flow rate is measured by a water counter and also by weighting; it's adjusted by a control valve.

3.1.4   Measuring equipment and data processing

Pressure drops are measured on each heat exchanger with differential pressure sensors, refrigerant flow rate is measured with a Coriolis flow meter, and humidity is measured with relative humidity sensors. Data acquisition is performed with 3495A IMP/PC system at a sample rate of 1 Hz.

3.1.4.1   Temperatures

The temperatures are measured using T-type thermocouples (copper-constantan). The reference temperature is 0°C and it is given by a water ice mixing. The accuracy is estimated to be ±0.2 K.

For air flow temperatures, since radial temperature gradients can occur, a net of thermocouples is used (Figure 5). The dispersion σ between all thermocouples is the mean difference between each measured temperature and mean value for all the thermocouples. This leads to a σ < 0.3K at the supply of the evaporator/condenser, and to a σ < 0.7K at the exhaust of the evaporator/condenser.

In order to reduce conduction uncertainties, refrigerant and water temperatures are measured with thermocouples installed in glove fingers, as indicated in Figure 5.
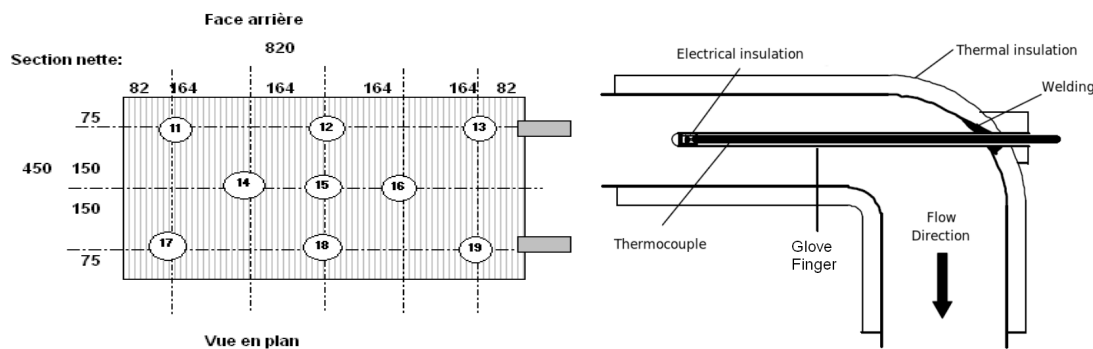

Figure 5 Temperature measurement in an air line (left) and in a refrigerant pipe (right)

3.1.4.2   Air flow rate measurements

All air flow rates are measured with nozzles and differential pressure sensors, according to the ISO 5167-1980 standard.

Air mass flow rate is computed as follows [3]:

$$\dot{M} \cdot (1 + w) = C_d \cdot A_{int} \cdot \varepsilon \cdot \sqrt{2 \cdot \rho \cdot (1 + w) \cdot \Delta p}$$

Where M is the dry air mass flow rate, w is the humidity ratio, A_{int} is the orifice area, ρ is the dry air density and Δp is the measured pressure drop across the nozzle.

C_d (the flow coefficient) and ε (compressibility coefficient) are calculated according to the ISO 5167 standard as a function of the Reynolds number and of the nozzle diameters.

3.2   Test results

Several steady-state performance points are obtained on both the evaporator and the condenser. For each test, three heat balances are established: on both heat exchangers and on the compressor respectively. This allows checking the consistency among the measurements. Table 1 shows an example of results obtained on the evaporator.

Supply air temperature	26.9 °C
Supply relative humidity	48.1 %
Air flow rate (at supply conditions)	2809 m³/h
Evaporating temperature	4.3 °C
Superheating at evaporator exhaust	3.2 K
Sub cooling at expansion valve supply	1.3K
Capacity on refrigerant side (reference value)	28.5 kW
Refrigerant flow rate	0.207 kg/s
Lubricant flow rate	0.0038 kg/s
Refrigerant side pressure drop (including distribution)	1.52 bar

Exhaust air temperature	7.6 °C
Exhaust air relative humidity	96.5%
Air side pressure drop	156.1 Pa
Heat balance residue on the compressor	-1.25 %
Heat balance residue on the air-heated evaporator	2.24 %
Heat balance residue on the water-cooled condenser	-0.86 %

Table 1 Example of test results on the evaporator

4. TESTING OF A ROOM AIR CONDITIONER

Previous sections described the measurements performed on HVAC components. In some cases, measurements on the components alone are not sufficient, and the whole HVAC system has to be characterized. The section describes the experimental investigation of reversible room air conditioner (RAC). The testing method is based on a double energy balance [4]:

- The *air side* energy balance ("calorimeter" method) consists in installing each (indoor and outdoor) unit inside a calorimeter. Each calorimeter contains all (water and heat) sources and sinks, required to absorb the emission of each unit and to maintain the required environmental conditions (air temperature and humidity).
- The *refrigerant side* energy balance ("enthalpy method") is based on the determination of the refrigerant enthalpy flow rate supplied to each element of the RAC (compressor, condenser, expansion valve and evaporator). This is made possible thanks to the use of a set of temperature and pressure sensors and of a Coriolis flow meter, introduced in the refrigerant circuit.

4.1 DESCRIPTION OF THE TEST BENCH AND TEST METHOD

Testing conditions are fixed in priority according to the international standard ISO 5151 standard. In order to cover a larger domain of use, six other combinations of test conditions are also considered.

The "indoor" test room is a volume (conform to ISO 5151), in which the required test conditions are maintained within specified tolerances (0.5 K for the temperatures). The air velocity is never exceeding 2.5 m/s near the tested equipment. The "outdoor" test room also shows a sufficient volume (conform to ISO 5151) to avoid any perturbation of the "normal" air circulation pattern. The distances between all walls, except for the floor, and all equipment surfaces are larger than 0.9m. The manufacturer's installation instructions are also carefully respected.

Figure 6 View of the RAC outdoor unit (left) and indoor unit (right)

4.1.1 Calorimeter method

The calorimeter provides a method for determining the capacity simultaneously on both indoor and outdoor sides of the equipment. In cooling mode, this method is used only to check the air-conditioning unit performances obtained by the refrigerant-enthalpy method. Heat and water mass balances are used to determine the indoor unit capacity.

An electrical heater and a steam boiler provide the sensible and latent heat respectively.

The saturated steam is superheated in order to compensate the ambient heat losses with help of a super-heater.

A power transducer measures the sensible heat input.

The latent heat input is determined by measuring, the amount of water consumed by the steam boilers.

The outdoor unit capacity is also determined in order to check indoor side heat balance. The outdoor air is cooled or heated by a fan-coil unit. The cooling or heating power is determined by a water side energy balance. Supply and exhaust water temperatures are measured by thermocouples located in glove fingers; the water flow rate is measured every 15 minutes with the help of a balance and continuously checked with the help of a counter.

The calorimeter is completely insulated. An insulated wall separates also the "indoor" and "outdoor" rooms of the calorimeter. The air temperatures are controlled in the air channels surrounding the calorimeter. Heat gains or losses of all calorimeter walls are determined with the help of heat flow meters. Air temperatures and relative humidity are measured at the supply and at the exhaust of each (indoor/outdoor) unit. Globe temperatures are also measured at different points. The main sizes and the general arrangement of the calorimeter are shown in Figure 7.
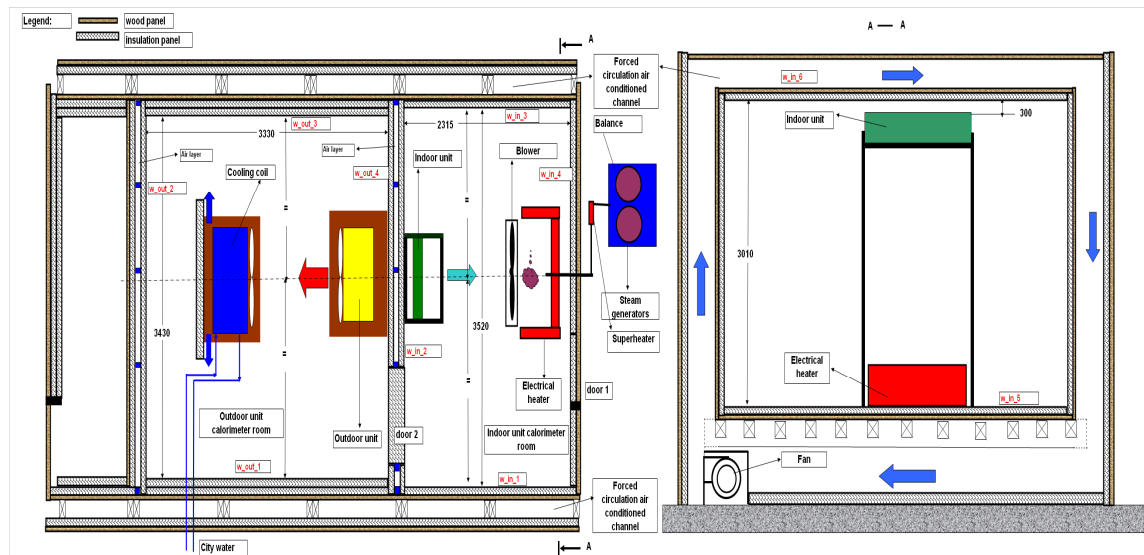

Figure 7 General view of the calorimeter rooms (cooling mode arrangement)

4.1.2   *Refrigerant Enthalpy Method*

Temperature and pressure measurements are used to determine the enthalpy change through each component. The refrigerant mass flow rate is measured with help of a Coriolis flow meter, located downstream of the condenser, in the liquid line. Enthalpy changes and flow rate are combined together in order to determine the cooling and heating capacities.

4.2   Test results

Examples of test results obtained with one RAC are presented in Table 2.

The results available show among others that:
- The differences between both experimental methods are currently not over-passing 5 %;
- The Energy Efficiency Ratio (EER) coefficient in *cooling* mode is here varying from 2.9 to 4.6, according to the class and mainly according to the conditions of use;
- The EER coefficient in *heating* mode is varying from 2.7 to 3.7;

The main "bottle neck" for increasing EER seems located at the level of the condenser in both modes, i.e. at the level of the outdoor heat exchanger in cooling mode and at the level of the indoor heat exchanger in heating mode. In the present case, indeed, the main difference between "high" and "medium" classes consists in an increase of area of the outdoor heat exchanger.

No	Test	Indoor temperature	Indoor relative humidity	Outside temperature	Indoor unit cooling power			Evaporating Temperature	Exhaust Air Temperature -Evaporator	SHR	Outdoor unit heating power			Condensing temperature	Exhaust air temperature - Condenser
					Enthalpy Method	Calorimeter. Method	Rel diff				Enthalpy Method	Calor. Method	Rel diff		
		°C	-	°C	W	W	%	°C	°C	-	W	W	%	°C	°C
1	120207A	27,08	0,44	35,35	2225	2255	1,37	11,39	12,58	0,846	2666	2588	-2,93	44,96	39,4
2	160207A	20,76	0,5283	27,28	2786	2806	0,7357	4,186	5,561	0,703	3335	3322	-0,3897	39,56	32,17
3	260207A	28,78	0,4016	45,99	1860	1852	-0,4195	15,15	15,93	1	2371	2289	-3,46	54,11	49,79
4	130207A	27,0067	0,31	33,96	2326	2379	2,261	9,816	10,87	1	2797	2692	-3,754	44,03	38,15
5	140207A	27,396	0,61	33,73	3262	3216	-1,417	11,9	13,33	0,513	3966	3926	-0,9961	47,5	39,84
6	220207A	23,57	0,6074	30,42	2962	2906	-1,892	8,008	9,356	0,58	3565	3634	1,933	43,36	35,83
7	210207A	23,37	0,3453	31,01	2149	2209	2,785	6,944	7,994	1	2578	2572	-0,2088	40,79	35,03
8	150207A	27,46	0,4463	20,86	2370	2443	3,074	10,57	12,1	0,797	2619	2584	-1,327	30,18	24,59
9	230207A	20,88	0,5409	20,38	2397	2389	-0,3558	5,481	6,698	0,684	2748	2792	1,578	30,4	24,24
10	Dry_nom	27,046	0,2723	36,6	2528	/	/	9,975	11,17	1	3132	/	/	47,39	40,99

No	Test	Power Consumption of the RAC	Power consumption of the compressor	Compressor Effectiveness	EER	Compressor Rotation Speed**	Power Consumption of the evaporator fan	Level speed of the fan	Evaporator fictitious effectiveness	Evaporator fictitious global heat transfer coefficient	Condenser fictitious effectiveness	Condenser fictitious global heat transfer coefficient
		W	W	-	-	tr/min	W	-	-	[J/K]	-	[J/K]
1	120207A	584,1	507,1	0,691	3,8	2320	11,02	Medium	0,8372	651,2	0,3519	278,5
2	160207A	741,3	664	0,6951	3,8	3438	11,24	Medium	0,8718	600,8	0,3601	298,6
3	260207A	639,8	561,7	0,6542	2,9	1974	12,09	Medium	0,943	414,9	0,3242	238,5
4	130207	609,2	530,8	0,7046	3,8	2522	12,47	Medium	0,9838	1526	0,3542	285,7
5	140207A	885,9	809,3	0,6879	3,7	3481	10,6	Medium	0,8661	726,1	0,3786	303,9
6	220207A	796,1	719,4	0,6816	3,7	3356	10,75	Medium	0,8686	642,7	0,3695	299
7	210207A	551,4	473,1	0,7044	3,9	2417	12,32	Medium	0,8929	743	0,3506	276,9
8	150207A	340,5	313,6	0,6299	7,0	2142	10,92	Medium	0,8201	571,2	0,3752	328,8
9	230207A	422,9	346	0,7502	5,7	2544	10,88	Medium	0,8785	581,4	0,3609	311,8
10	Dry_nom	710,5	630,7	0,7114	3,6	2731	13,81	High	1	5340	0,3374	281,6

Table 2 Examples of test results on the room air conditioner

CONCLUSION

Several experimental methods are presented in this paper that permit to determine accurately the performances of the tested components.

The calorimeter method allows measuring the ambient losses of the components, and allows, for example, performing a heat balance over the compressor. This heat balance can be used for checking the refrigerant and/or oil flow rate in the device.

Defining various and well pre-defined working conditions is of crucial importance. For that purpose, the design of an air network and of a refrigerant circuit are described, that are used to control the supply conditions (temperature, humidity, pressure) of the heat exchangers.

In the same manner, a double calorimetric room is used to define ambient conditions for the testing of the room air conditioner.

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