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MEASUREMENTS OF THE DYNAMIC PERFORMANCE AND BEHAVIOR OF AIR-CONDITIONING SYSTEMS USING A DYNAMIC TEST FACILITY

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ABSTRACT

Air-conditioning systems run under widely changing operating conditions. During their transient period of operation, they suffer from losses in capacity and COP, which are dependent on the magnitude and rate of the deviation of the real operating conditions from design conditions. To understand the system behavior under such dynamic conditions, a test facility that can impose transient loads as well as conducting dynamic measurements is needed. Most environmental chambers (calorimeters) used to test air-conditioners are unable to achieve this goal. A new test facility, the "Dynamic Simulator", has been designed, constructed, and verified for performing dynamic tests. It can replicate real operating conditions by interacting with the system being tested and reacting based on pre-determined time-dependant set points, measured system performance, and/or user specified events. This approach in testing the transient performance and behavior is most valuable in evaluating different control schemes and comparing different system configurations and refrigerants under fair and realistic conditions and in evaluating reliability issues.

1. INTRODUCTION

During its actual course of work, the outdoor unit of a residential heat pump is subjected to ambient atmospheric conditions, including solar radiation. The indoor unit is subjected to the conditions inside the place where it is in, which are close to atmospheric conditions if the heat pump system has been off for a long period of time. When the compressor is then turned on, the air surrounding the indoor unit is soon to be cooled down (or heated up in winter), while the outdoor unit remains subjected to ambient atmospheric conditions. The period from the start of the system (the cut-on) until the air in the conditioned space reaches its designed conditions, (as well as any subsequent period the system takes to readjust to steady state after a change in load), is called a transient period.

In the case of an automotive system, the indoor unit is placed under the dash-board inside the cabin which has a substantial area made of glass. Therefore, by what is known as the glass-house effect, the temperature that exists inside the cabin at the beginning of the cool down period is higher than the ambient atmospheric temperature, and might reach 60°C (140°F) in a 35°C (95°F) environment (Meyer, 2002). This is called the "hot-soak" condition. On the other hand, the outdoor unit is placed next to the vehicle engine and therefore is affected by the heat generated from the engine.

There are two types of loads to which a heat pump is subjected during steady state operation (ASHRAE, 2001). Space loads, such as heat transfer, solar radiation, and heat generated by the occupants, alter the condition of air inside the conditioned space. Outdoor-air loads, such as infiltration air heat or ventilation air heat, result from the change in outdoor air condition. The loads imposed on a heat pump system are, therefore, continually varying by nature. They dictate the parameters of operation of the heat pump, such as the high-pressure level and its corresponding temperature, low-pressure level and corresponding temperature, refrigerant quality at exit of heat exchangers, and refrigerant charge inside each of the cycle components. These parameters are unique for each set of loads imposed on the heat pump. Automotive systems have even more variables; the rotational speed of the compressor, which is dependent on the vehicle engine rotational speed, varies between a low value in idling case and a high value in driving case. The outdoor coil face velocity also changes, within limits, according to the change of vehicle traveling speed.

One of the most common ways to handle the variation in loads is to use control devices, such as thermostatic expansion valves (TXV), electric expansion valves, or variable displacement compressors. . Each time a control device reacts to a change in load, the heat pump comes to a balance at a different set of operation parameters.

Another way to control the capacity of a heat pump is to cycle the compressor on and off depending on a signal from a thermostat placed inside the conditioned space to sense its temperature. When the compressor is turned off, there is nothing else in the system to maintain the high-pressure level in the outdoor unit and the low-pressure level in the indoor unit; therefore the refrigerant starts to migrate from the condenser to the evaporator passing through the expansion device. Some expansion devices allow fast migration, such as the capillary tube and the orifice, and some allow very little or minimum migration, such as the thermostatic expansion valves, especially those with no bleed port. Migration continues for some time until the pressures are equalized. Afterwards, migration will continue as a result of temperature difference as long as there is one. The refrigerant also carries some energy with it to the evaporator. Whether this energy will be transferred to the evaporator air, or remain in the refrigerant, depends on the temperature of the evaporator air and the evaporator. If the evaporator heats up to a temperature higher than the air temperature, it will heat the air, and then this energy will represent extra load on the system when it is switched on. The amount of energy that is carried with the migrating refrigerant to the evaporator air was estimated by Rubas and Bullard (1995) for a household refrigerator to be 4% of the steady state capacity in case of liquid migration, and 7% of the steady state capacity in case of vapor migration.

We therefore conclude that during any transient period a heat pump is subjected to additional loads that materialize in redistribution of the refrigerant, as well as the lubricant oil circulating with it, among the different components of the system, readjusting the operating parameters, such as the temperature of the different parts of the system and the temperatures and pressures of the refrigerant to their new operating values, and reconditioning the thermal mass of the conditioned space to the steady state air temperature. These loads are, by nature, time-dependent. They are at their peak at the beginning of the transient period and decrease with time until they diminish. Therefore the case during the transient period is similar to the case of an undersized system working at a lower efficiency than the design one.

The performance and behavior of the system during the transient period is dependant mainly on the performance of the compressor and expansion device and the configuration of the system such as the presence of equipment such as accumulator, receiver, suction line heat exchanger, or oil separator. These components affect the length and the power consumption during the transient period (Mulroy and Didion, 1983). The COP of the system during the transient period suffers from a loss whose magnitude depends on the deviation of the real operating conditions from the design conditions. This loss is called the transient loss. However, what is called loss might also be thought of as potential saving.

The magnitude of the cyclic loss or potential saving is even more underscored in the automotive application largely due to the varying rotational speed of the compressor. Automotive systems need to be designed such that they can deliver acceptable capacity at a low compressor RPM, thus, the systems usually have charge management devices, such as a suction accumulator or a receiver (Althouse *et al.*, 2000).

To capture the dynamic behavior of a heat pump, a test facility should be able to impose customized dynamic loads on both the outdoor side and the indoor side of the heat pump. The test facility should be able to: (a) run weather cycles to simulate change in outdoor air conditions, (b) run drive cycles to simulate the varying rotational speed of an automotive compressor, (c) simulate the thermal storage load of the conditioned space, (d) simulate changes in space loads resulting from a change in number of occupants, equipment, or lighting in the conditioned space, and (e) control the percentage of fresh air mixed with the supply air and has controllable evaporator fan speed to simulate different user settings.

Also, for the test data to be meaningful, the test facility should be able to acquire fast measurements for the properties of the refrigerant and the air, and the temperature of the metal of the system itself.

2. THE DYNAMIC SIMULATOR

A "Dynamic Simulator" has been designed, constructed, and verified for the purpose of conducting dynamic tests on heat pump systems. The dynamic simulator is a test facility that can interact with the system under test., in other words feels the system under test, and reacts accordingly to simulate real-world conditions. It gathers information about the system under test through measurements, such as the evaporator air outlet temperature. It also accepts user input through its graphical user interface, such as the thermal storage parameters of the conditioned space or various loads on the heat pump being tested. It can impose time-dependent set points on the operating conditions of the heat pump, such as temperature and relative humidity cycles and drive cycles. It also allows different evaporator fan user settings. The dynamic simulator was built so that it can accommodate any future additions or changes that will prove to be necessary. It is physically composed of two parts: the indoor simulator and the outdoor simulator, as shown in Figure 1. The outdoor unit of the system under test is placed in the outdoor simulator, which is a (5 x 5 x 3 m) environmental chamber that includes inside it an air duct attached to a fan. The outdoor unit of the test system is placed either inside the duct to control the air flow across it, as in the case of an automotive system, or outside the duct to simulate a free air flow around it, as in the case of residential units. The indoor unit of the system under test is placed inside the indoor simulator, which is a closed air loop, so that both the air flow and air temperature before and after the test section can be measured accurately. Both the outdoor simulator and the indoor simulator have air handlers to control the properties of air inside them. Both air handlers are more or less the same, except that for the indoor simulator, the dehumidifier is after the cooling coil and for the outdoor simulator both the humidifier and the dehumidifier are separate from the cooling and heating coils. An example air handler is shown in Figure 2, together with the control imposed on it.

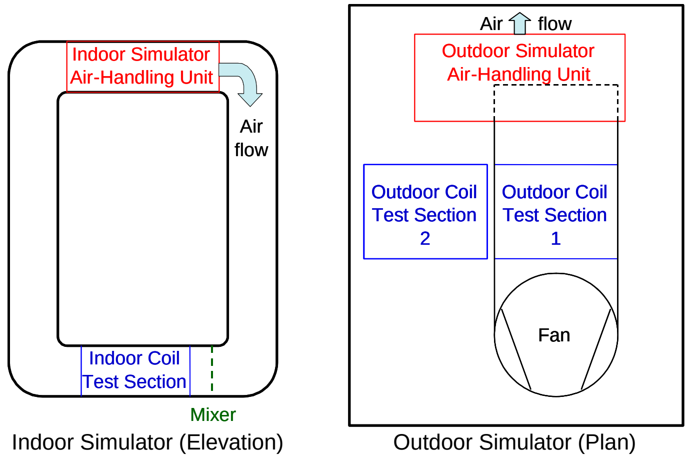

Figure 1 A Schematic of the Physical Construction of the Dynamic Simulator and Test Sections

There are two steps of control implemented on the dynamic simulator; viz software control and hardware control that is shown in the lower part of Figure 2. The software, which was written specifically for the dynamic simulator, represents also the graphical user interface.

The user enters temperature cycles, relative humidity cycles, and drive cycles to the software in the form of a matrix that has the process variable values in one row and corresponding values of time in another. The user also enters a cabin model to the software in the form of an equation that may include heat transfer load, infiltration load, thermal storage load and solar load. The software works in time steps called the control cycle - also specified by the user. For each control cycle, the software gets signals from temperature, relative humidity, airflow rate, and compressor RPM sensors which then process all the inputs and produces a set of set points for the different components of the air-handlers as well as the fans and compressor motors. Each set point (S) is further adjusted according to Equation (1).

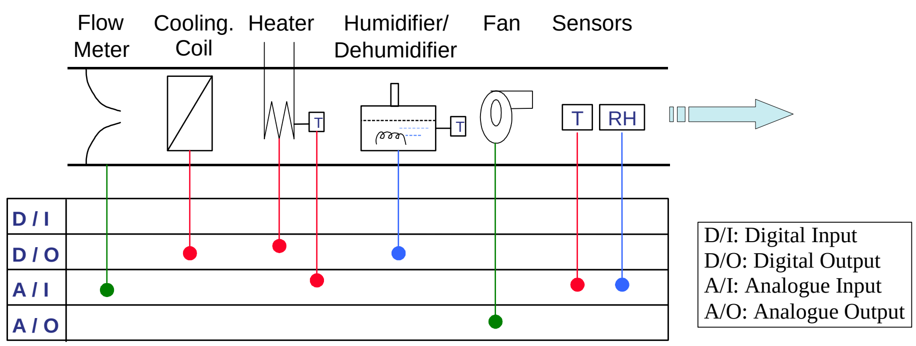

Figure 2 The Air-Handling Unit of the Dynamic Simulator with Implemented Controls

$$S_{adj} = S + f_{PID}\,\{(1-a)\,e + a\,e'\} \tag{1}$$

where,

f_{PID} is a proportional plus integral plus derivative function,
a is anticipation factor, a constant specified by user, varies between *0* and *1*.
e is the error, i.e., the difference between S and the measured process value, and
e' is the difference between S of the next step (if known) and the process value.

The P, I, and D parameters as well as the control cycle and the anticipation factor all need to be optimized by the user for best dynamic performance. The adjusted set point (S_{adj}) is then sent to the hardware control. The hardware for controlling each of the fans and compressor motors is a motor inverter. The hardware for controlling each of the relative humidity and the temperature is a dual digitized output PID controller. The hardware controller digitizes its output by turning on and off either or both of its outputs for short periods of time that are in proportion with the capacity that is needed. For example, the outputs of the relative humidity controller turn the humidifier and the dehumidifier on and off. Figure 3 is a simplified schematic of the condensing unit that drives the cooling coil shown in Figure 2. The condensing unit is a three-pipe hot gas bypass unit with quick cycling solenoid valves that allow a continuous control over the capacity. For temperature control, a cooling controller output simply means turning the electric heater off, closing the hot-gas solenoid, and opening the liquid-line solenoid to allow cold refrigerant to pass through the cooling coil of the air-handler. A heating controller output means turning the electric heater on, opening the hot-gas solenoid, and closing the liquid-line solenoid to direct the hot refrigerant from the compressor discharge directly to the coil.

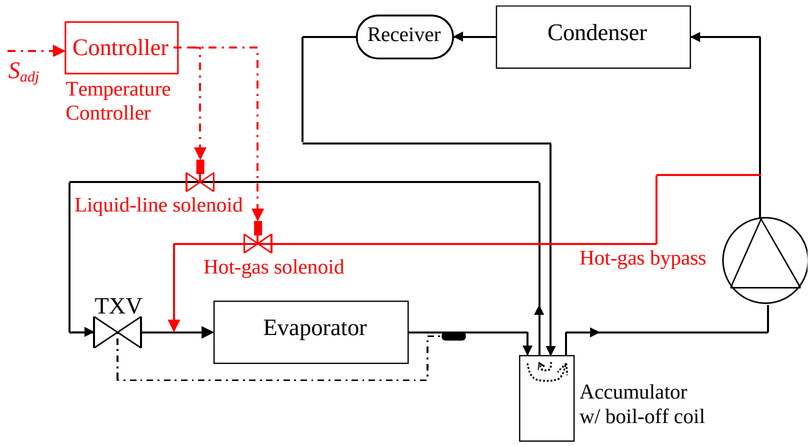

Figure 3 Schematic of the Condensing Unit

In summary, having a good control on a process variable is a procedure that includes several steps. It begins with having a robust capacity control over the equipment and making sure that this capacity is enough for the requirements. Then all the instrumentations should be chosen carefully to be fast enough for the readings to be meaningful and the instrumentations should be accurately calibrated. Then, having two steps of control, with well-tuned parameters, goes a long way in bringing the process variable close to the set point.

3. TEST SYSTEM

The R134a automotive system shown in Figure 4 has been assembled inside the Dynamic Simulator. An automotive system was chosen because those systems offer the biggest challenge in terms of control, later on in the project this system will be used to asses control issues.

The system has a serpentine evaporator, fin-and-tube condenser, manual expansion valve, suction accumulator, and an open-drive compressor. Care has been taken to make the lines as short as possible and to raise the compressor to almost the same level as the condenser in order to resemble the actual installation. The system is equipped with one mass flow meter, torque and RPM meters, and also pressure sensors and in-stream thermocouples before and after every component as shown in the Figure 4. Other than these measuring instruments the system is also equipped with thermocouples along the circuits of both heat exchangers, thermocouples on both the compressor and the accumulator shells, and both in-stream and surface thermocouples along the vapor line. All in-stream thermocouples are thin gauged with exposed junctions to ensure fastness of measurements. For the airside, the dry bulb temperature, relative humidity, and pressure are measured before and after the evaporator, as well as the airflow rate. Also the temperature and the pressure drop are measured around the condenser.

All instruments were calibrated and the saturation temperature and pressure values were checked against each other to check the accuracy of measurements. Moreover, roughly after each test, the capacities as calculated from the airside and from the refrigerant side were checked and the error was kept below 5%.

4. DYNAMIC SIMULATOR VERIFICATION

Tests were conducted with the purpose of verifying the interaction between the dynamic simulator and the heat pump system being tested. Four categories of tests where conducted. In the first category, the unloaded tests, parameters such as temperature, relative humidity, airflow rate, and compressor RPM were controlled according to a pre-set profile while the test system is off to check the accuracy of dynamic simulator control. Figures 5 and 6 show examples of this category of tests. It is clear from the figures that the absolute error in controlling temperature was within ± 0.5°C (1°F) and the absolute error in controlling relative humidity was within ± 2%.

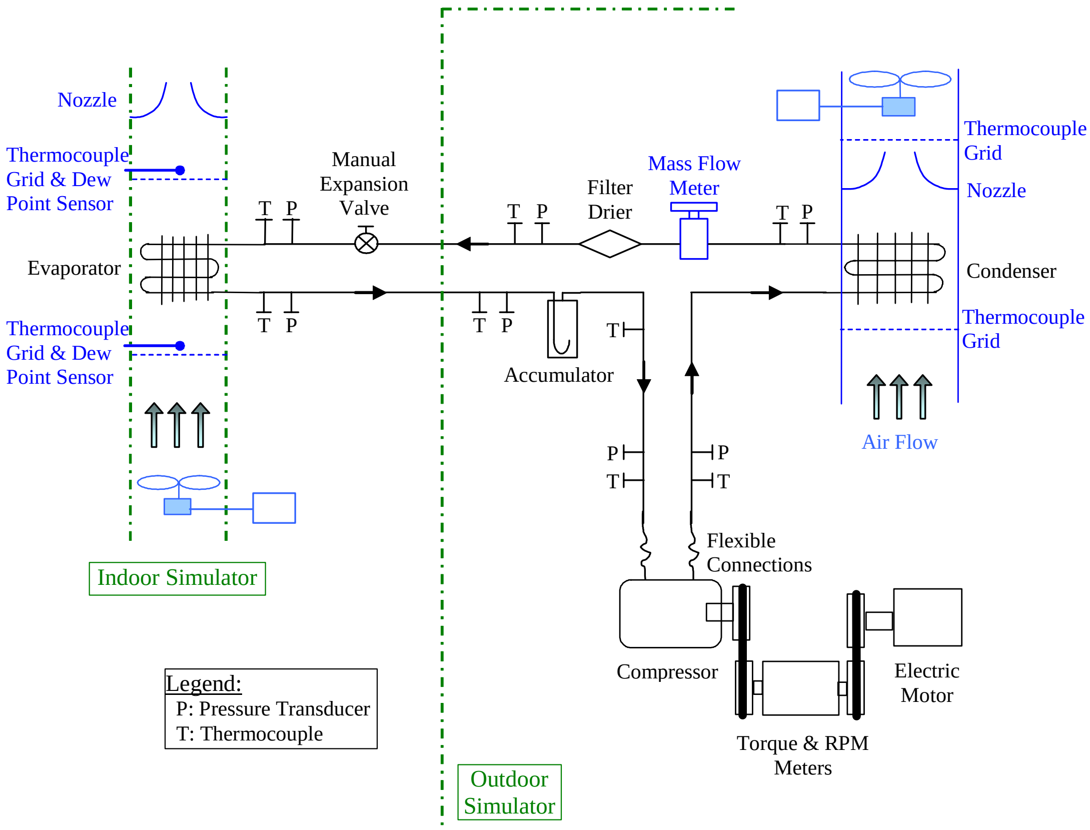

Figure 4 A Schematic of the Automotive System under Test

The second category of tests is the loaded tests category, in which, the test system was running while the dynamic simulator imposed a pre-specified temperature pull down profile on the indoor side. Figures 7 and 8 show results of a test where the conditions were: 35°C (95°F) dry ambient air and no soaking. The compressor was running at 2100 RPM and the clutch was engaged just at the start of the test. Figure 8 shows the instantaneous sensible and latent capacities of the system, the refrigerant side capacity, and COP as calculated from the air side. Superheat at the evaporator outlet was lost nearly 13 minutes into the test.
In the third category, the New European Drive Cycle (NEDC) (Wertenbach, 2003) was imposed on the system and the clutch was engaged at the beginning of the test. Figures 9 to 12 show an example test where the conditions were 100 % fresh air return at 30°C, 60% relative humidity and no soak. Figures 9, 10, and 11 show how do the refrigerant temperatures, refrigerant pressures, and air temperatures vary as a result of the cycle, respectively. Figure 12 shows the airside sensible and latent capacities as well as the refrigerant side capacity and the COP as calculated from the airside.
In the fourth category of tests, the cabin model tests, the dynamic simulator imposed a load on the system to simulate a cabin model. At this point, the cabin model is calculated according to the simple Equation (2); later on in the project a real cabin model will be incorporated.

$$Load = Const.(T_{amb} - T_{panelout}) + Const.(T_{core} - T_{panelout}) + Solar\ Const. \tag{2}$$

where,

T_{core} is effective temperature inside the cabin, given by a pre-specified profile, and
$T_{panel\ out}$ is evaporator outlet temperature, measured by the simulator.

The first term on the right hand side in Equation (2) represents the combined load of heat transfer and infiltration or ventilation, whereas the second term represents the thermal storage load.

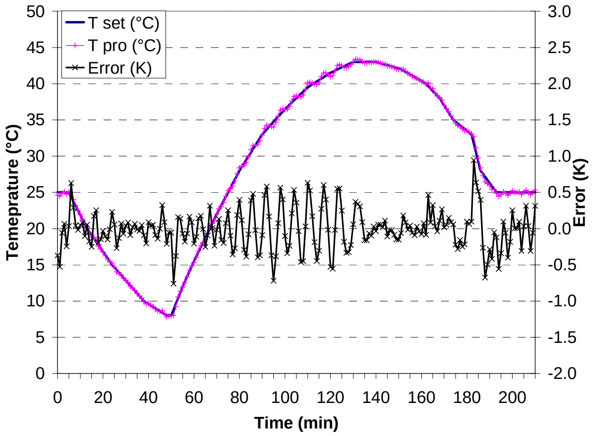

Figure 5 Temperature Control in Outdoor Simulator

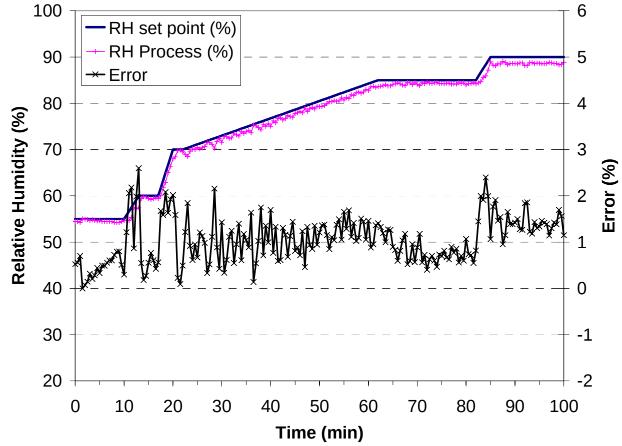

Figure 6 Relative Humidity Control in Outdoor Simulator

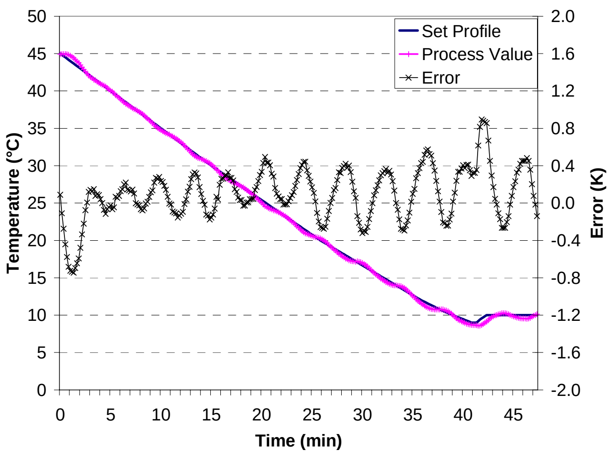

Figure 7 Pull Down during Loaded Test in the Indoor Side

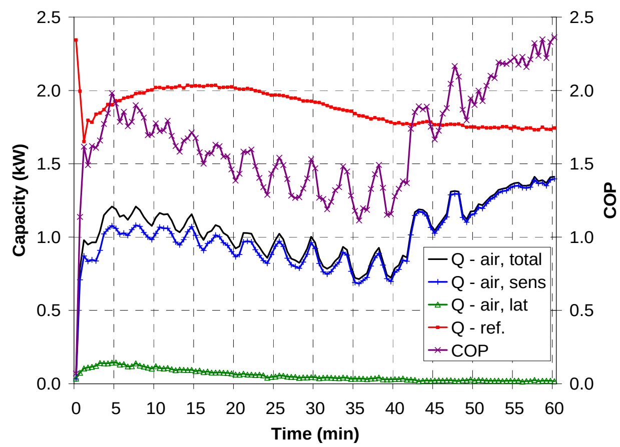

Figure 8 Capacities and COP During Loaded Test

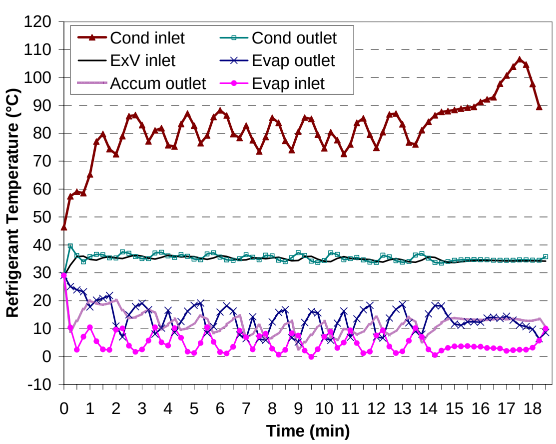

Figure 9 Refrigerant Temperatures during NEDC

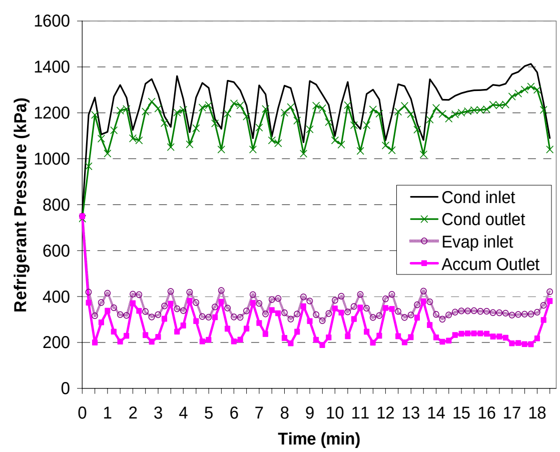

Figure 10 Refrigerant Pressures during NEDC

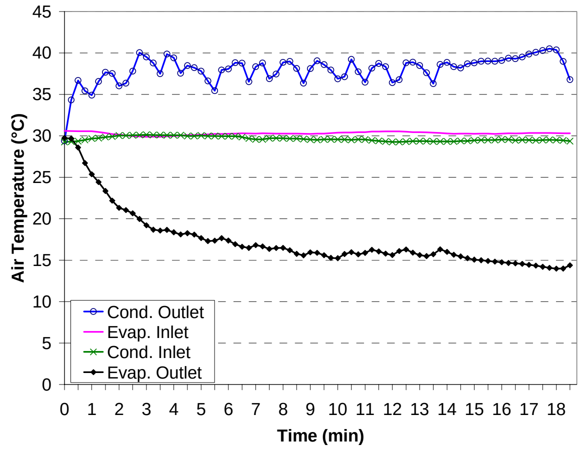

Figure 11 Air Temperatures during NEDC

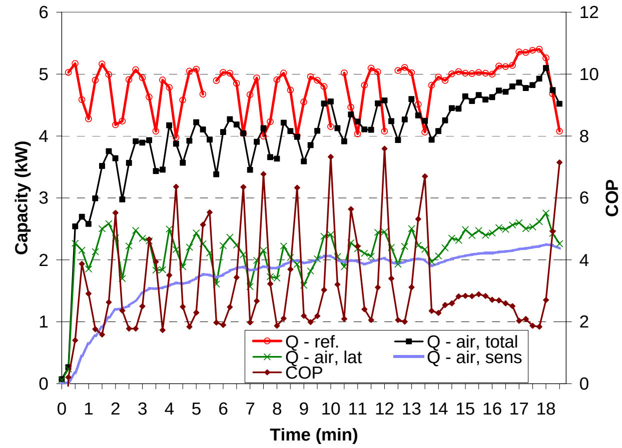

Figure 12 Capacities and COP during NEDC

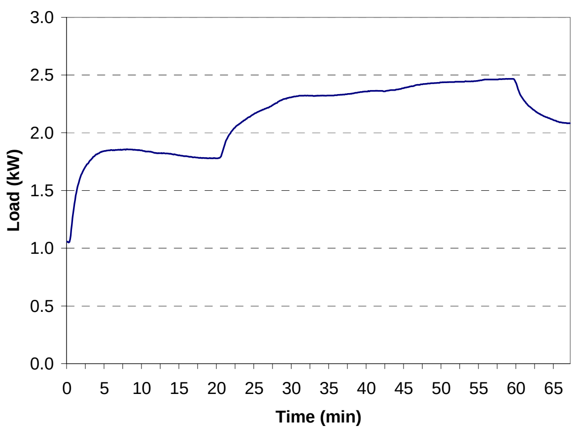

Figure 13 Cabin Load during Cabin Model Test

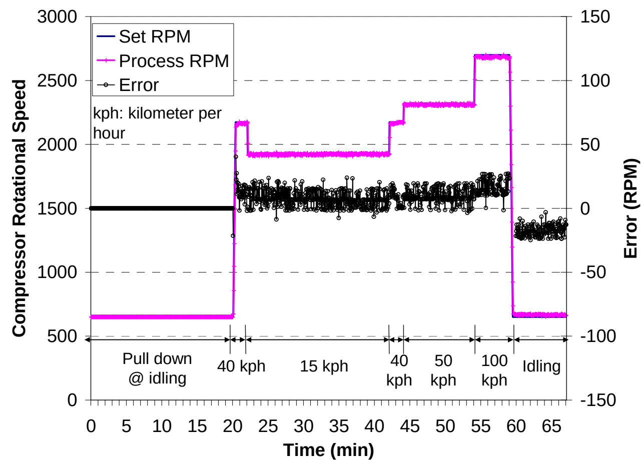

Figure 14 Drive Cycle for Cabin Model Test

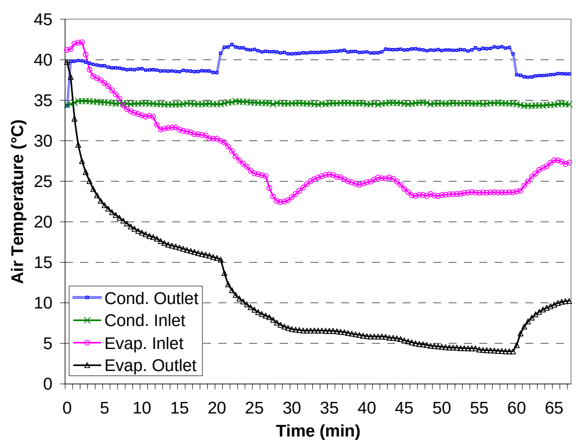

Figure 15 Air Temperatures for Cabin Model Test

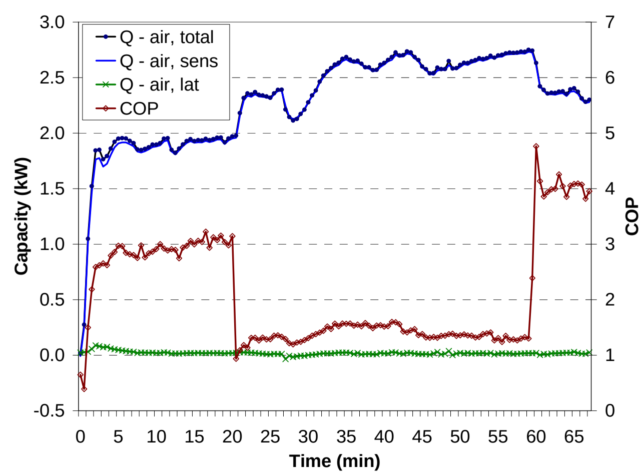

Figure 16 Capacities and COP During Cabin Model Test

The load is presented in Figure 13 versus time. After the heat pump has pulled down the evaporator outlet air to 15°C at idling speed, a simple drive cycle was started, as shown in Figure 14. Figures 15 and 16 shows some results of a test where the conditions were 35°C dry ambient air and 5°C soak. Figure 15 shows how the air temperatures vary as a result of the cycle. Figure 16 shows the airside sensible and latent capacities as well as the refrigerant side capacity and the airside COP.

5. CONCLUSIONS

Heat pump systems are subjected to time-dependent loads during the transient period of operation. These include redistribution of refrigerant and oil among the different components of the system, readjustment of operating parameters such as the temperature of the different parts of the system and the temperatures and pressures of the refrigerant to their new operating values, as well as reconditioning the thermal mass of the conditioned space to the steady state air temperature. During this period the COP suffers losses. To test the dynamic behavior of a heat pump, the dynamic simulator is able to run weather cycles, run drive cycles in case of automotive systems, simulate the thermal storage load of the conditioned space, simulate changes in space loads, and allows different user settings including fan speed and percentage of fresh air. It also is able to acquire fast measurements for the properties of the refrigerant and the air, and the temperature of the metal of the system itself.

Special software was written specifically for the dynamic simulator to represent the graphical user interface and in addition to serving as process control, it also serves the purposes of process monitoring, data acquisition, and graphical display. The software processes the data, sends signals with set points to the control hardware and receives feedback from it. The software monitors whether the process variables are really following the set points, and if not, the software sends signal to the PID controller to adjust its outputs.

The dynamic simulator has been verified for the purpose of running real-world dynamic tests. It controls the operating conditions according to the desired profile within acceptable tolerances. It incorporates a model for the conditioned space. An automotive system tested by the dynamic simulator works just as if it is installed in a real operating car.

6. FUTURE WORK

The dynamic simulator is currently being used to test R134a systems. Future work includes testing different cycle configurations including an electronic expansion valve. Also R134a heating mode tests will be conducted. Then, other refrigerants, such as CO_2 and R152a will be tested and compared to R134a. Among the expected outcomes of the research project is evaluating different control schemes and reliability issues.

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