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DYNAMIC MODELS FOR AIR CONDITIONING SYSTEMS AND REGULATION STRATEGY

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Document Change Log

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0	0	October 2003	Draft
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CONTENTS

Symbols and abbreviations

Symbol	Description	Unit
Cp	specific heat	J/kg/°C
Dh	hydraulic diameter	m
F	mass flow rate	kg / s
h	heat transfer coefficient	$W/m^2/°C$
h	specific enthalpy	J / kg
$\dot{h}$	enthalpy flow	W
Hr	relative air humidity	%
K	coefficient of proportionality	
Lv	latent heat	J / kg
M	mass	kg
N	speed rotation	rpm
Np	number of tubes in a row	-
Nc	number of cell for one tube	-
Nu	Nusselt number	-
n	number of cells in the exchanger	-
p	Laplace operator	-
P	pressure	Pa
Pw	power	W
Pr	Prandtl number	-
Re	Reynolds number	-
S	Surface	m^2
s	step fin	m
St	Stanton number	-
ST	distance from the centers between two tubes in the same row	m
SL	distance from the centers between two tubes of adjacent rows	m
T	temperature	°C
t	time	s
U	energy	J
V	volume	m^3
Wa	absolute air humidity	kg of water / kg of dry air
Wv	absolute vapor water weight	kg vapor / kg of dry air
Wl	absolute liquid water weight	kg liquid / kg of dry air
λ	thermal conductivity	W/m/°C
ρ	density	kg/m^3
τ	time constant	s
Θ	time delay	s

Subscripts and abbreviations

a	air
cond	vapor condensation
cf	cold fluid cooling the exchanger
cell	cell of the exchanger
fct	Adersa's function library for air properties calculations
in	variable at the inlet of a component
l	liquid of water
loss	heat or mass losses
mes	measured variable
mv	manipulated variable
o	outdoor
out	variable at the outlet of a component

p	HVAC process
perturb	perturbation coming from losses
ref	reference for the enthalpy calculation of moist air
SP	set point
sat	state of saturation of the moist air
vapor	vapor of water blown by the humidifier
v	vapor of water
w	wall of the heat exchanger

1. INTRODUCTION

The TN introduces to the principles of predictive command applied to air conditioning systems. There are more and more processes where the air quality must be controlled and managed to obtain desired temperature, humidity and pressure. We proposed a regulation based on representative models of the process that allowed a great precision on the measured variables.

The regulations actually found in industry are essentially PID controllers whose simplicity and cost are the main advantages. It will be enough if the result is not too much constraint. Here we suppose cases where the process must be accurately controlled despite non-linear behaviors and disturbances. A second goal is to minimize the consumption power becoming possible with this accuracy.

We choose a simplified process composed by a room whose temperature and humidity are managed by an air treatment process composed with a cold battery and a hot battery and a humidifier. Disturbances are applied to the room in order to test the regulation.

Others processes are used but the proposed approach would be the same. The simulator has to be enriched and essentially adapted to a specify process by experiments and model identification. Here are the tools preparing this industrial step.

2. DESCRIPTION OF THE PROCESS

The process is composed by the following components:

? the mixing chamber where recycling and outdoor air are injected into the process

? the cooler which controls the low temperature and dry the air

? the heater which controls the high temperature of the air

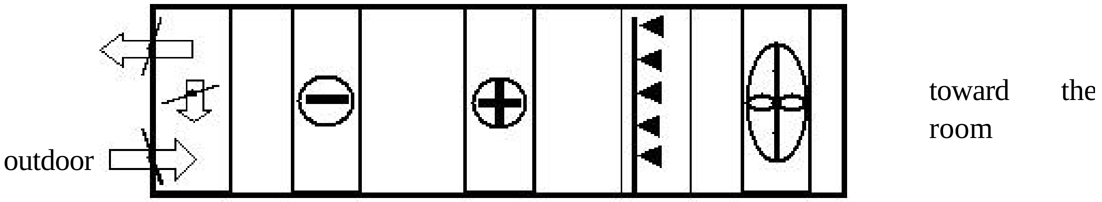
? the humidifier which enrich the water concentration in the air

? the ventilator assuming the air flow

? the room, goal of the air treatment whose temperature and humidity are specified.

The five first components compose the HVAC (heat ventilation and air conditioning) process. Others common components like filters, recuperator, pipes … are omitted but doesn't change the nature of the treated problem.

The schematic representation of the HVAC



Air treatment process

The actions on the process are:

- ? positions of the shutters acting on the ratio between new air and recycled ones
- ? heat power removed from the air by the cooler itself controlled by the cooling water flow
- ? heat power absorbed by air from the heater controlled by the hot water flow
- ? water steam injected into air flow
- ? rotation speed of the fan assuming the mass air flow

For each component the regulation computes the position of the actuators. The different actions must be supervised to follow the optimal trajectory and to avoid unnecessary opposed operations.

3. MODELING THERMAL PROCESS

Models are simplified models written to give a dynamic response at the mean controlled variables. Such models are usually used for designing and checking a regulation.

More complexes are the exchangers whose detailed model allows a fine study of the condensing process control.

The room pressure and pressure losses are not calculated because they act slightly with the thermal problem. The pressure control is then omitted in this study.
In some applications, the room pressure is controlled by the fan speed so that the mass flow rate of air may change. In this case, the dynamic behavior of all the components change with the air flow rate generated by the fan. This effect is a perturbation on the thermal system that the regulator will have to compensate.

3.1 MODELING PRINCIPLES

3.1.1 MODULAR DECOMPOSITION

There is infinity of air conditioning systems. To handle such a complexity, the global air conditioning system is split into smaller elementary systems. Each of these organic systems is connected to other elementary systems to build the global system.

Then a block with inlets and outlets represents each component. The various blocks are connected between them by informational, flow and effort connections.

The elementary blocks take into account various information types

- Particular characteristics of considered component: size, mass, structure …
- Information on the state of the component: on or off, actuator position
- power variables coming from other blocks: flows or efforts

This decomposition of the links is the application of the bond graph theory.

The component’s outputs will then be calculated from the physical equations representing the phenomenon, from the component parameters and from the inputs (outside influences).

3.1.2 AIR PROPERTIES

The list gives the main used variables:

Effort variables

-	P	Pressure
-	T	Temperature
-	Wv	Absolute vapor weight
-	Wl	Absolute liquid weight

Flow variables

-	Fa	Dry air flow
-	Fv	Vapor water flow
-	Fl	Liquid water flow
-	$\dot{h}$	Enthalpy flow

Another useful variables are available by calculation starting from these basic variables.

-	Wa	Absolute humidity
-	hr	Relative humidity
-	H	Enthalpy
-	Wsat	Saturate absolute humidity

3.2 COMPONENTS

The components, which we modeled, make it possible to reproduce the dynamic ones observed on the studied process. For that, we use two fundamental elements, which are the block "resistance", and the block "capacity".
These two basic blocks are supplemented by additional blocks, which extend the capacities of these two elementary blocks. Both remain however the base of dynamic construction of a dynamic process simulator.

The modeling of systems slightly more complex is done then by assembly of these 2 types of blocks and by addition of the functionalities necessary to these systems. We then obtain a new basic block, which could be to use in conjunction with other basic blocks to create a new block system.

Thus the progressive use of the component library enriches that library with new blocks necessary to our applications. This approach allows moreover the use of “under blocks” whose properties and qualities were validated by a former use.

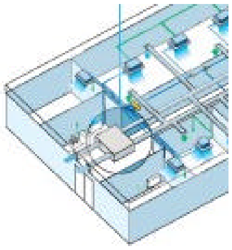
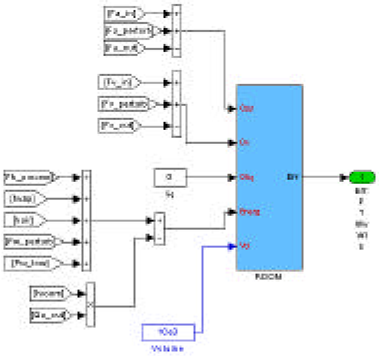
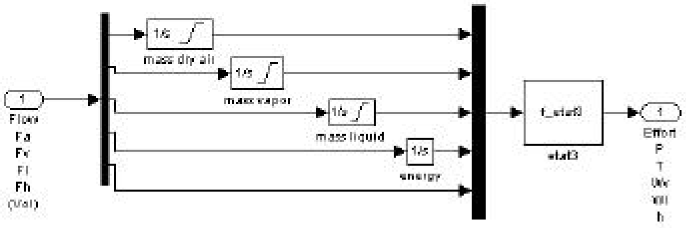
3.2.1 ROOM

Principle
The block "capacity" calculates the thermodynamic properties of the air contained in the room (Effort) starting from the properties of the air already present in this room and of the properties of the air flows entering and outgoing (Flow).

This component is the main element, which gives to the developed models, their dynamic character. Other models show a lower dynamic response. They don't influence the global response time of the whole system.

Field of application:
The calculation of the properties of air is done thanks to the thermal library developed by Adersa. The field of application of the block "capacity" is restricted with the field of application of this library.

Modeling:

Parameters and icon	**Block mass and energy balance**
? Volume ? Initial state: Temperature, humidity 	  "f_etat3" function of Adersa's library

Hypothesis:
The volume of the capacity is strictly positive, the pressure bound to the atmospheric pressure. Air state is assumed to be uniform (temperature and humidity).
The mass flow rate is calculated from the fan and the room pressure is not used for gas losses.

Physical equations:
Flows of air and energy are integrated in this module with respect of energy and mass balance coming from insulation and inside process.

$$Ma = \int \left(Fa_{in} - Fa_{out} + Fa_{perturb} \right) dt$$

$$Mv = \int \left(Fv_{in} - Fv_{out} + Fv_{perturb} \right) dt$$

$$Ml = 0$$

$$U = \int \left(Fa_{in} * h_{in} - Fa_{out} * h_{out} + Fa_{perturb} * h_{perturb} + Pw_{loss} + Pw_{perturb} \right) dt$$

The losses by insulation give a direct coupling of the room with outdoor conditions. This link has usually a weak dynamic effect.

$$Ploss = h * S * (T_{outdoor} - T_{room})$$

Other perturbations coming from the process and from staff inside the room emit heat and vapour. These perturbations are unknown.

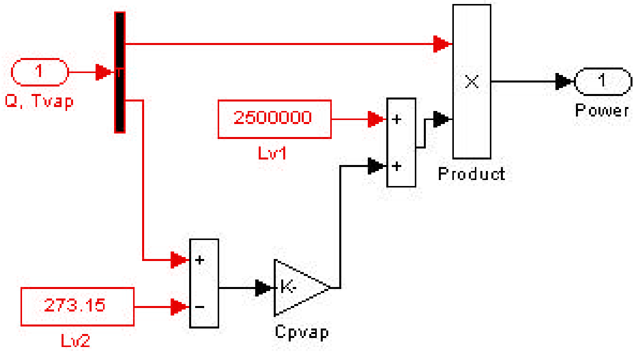
From the energy and mass account and knowing the volume of the capacity, the thermal library makes it possible to calculate the corresponding effort variables: pressure, temperature, and absolute humidity of vapour and liquid.

3.2.2 VAPOR HUMIDIFIER

Principle
The block "vapor generator" calculates the properties of the vapor at a temperature given to the atmospheric pressure. This vapor will then be used in the block humidifier to increase the water mass in the circulating air.

The mixture of the air circulating and the water vapor coming from this generator will produce a wetter and slightly hotter air.

Field of application:
The water vapor is injected at atmospheric pressure.

Parameters	**Block enthalpy conservation**
? Vapor temperature 	

Hypothesis
The coefficients of heat capacity of water liquid and the water vapor are constant. The latent heat of vaporization is taken with T_v and atmospheric pressure.

Physical equations
The production of vapor is made from a boiler but not included in the model. Steam vapor is assumed to be available instantaneously. The evaporation occurs at T_v and vapor is injected under atmospheric pressure inside the air flow raising the humidity.
The thermodynamic properties and conservation of mass and energy calculate air state.

Air properties leaving humidifier:

enthalpy flow $$\dot{ha}_{out} = \dot{ha}_{in} + F_{vapor} * \left(Lv + \left(T_{vapor} - T_{ref}\right) * Cp_{vapor}\right)$$

humidity $$Wv_{out} = \frac{Wv_{in} * Fa_{in} + F_{vapor}}{Fa_{in} + F_{vapor}}$$

temperature $$Ta_{out} = fct(ha_{out}, Wv_{out})$$

3.2.3 FAN

Principle
The fan produces the air flow into the air conditioning system. It permits to compensate all the pressure losses dues to the air friction in all the components of the system.
In the case of a simplified model the pressure losses are not calculated and the fan is only component whose flow is set to disturb the regulation.

Field of application
The flow has minimum and maximum values.

Parameters and icon	
	Fan is described by : ? a time constant τ taking into account the mass inertia ? a coefficient K assuming a constant linear relation between speed and flow.

The fan imposes the flow rate and speed variation drives the variation flow. Inertia of the body and the electrical motor are the dynamic behavior. Characteristic curves of the fan are hold by the manufacturer. Here (without a specific fan), we considered the following equation:

$$Fa = \frac{K}{tp + 1} N$$

3.2.4 COLD BATTERY

Principle
The cold battery is used to cool or to dry air. These two functions can run together but must be incoherent if the temperature set point at the exhaust is lower than the saturation temperature at the given humidity.

The exchanger is a tube bank exchanger. Outside the air goes through the cross section defined by the vertical row and becomes cooler and cooler. If the air temperature reaches the saturation point, water liquid appears on the fins and the air becomes dryer.

Field of application
The cold battery is the most difficult component to control because of the non-linearity due to the condensation phenomenon. To represent this non-linearity we use a spatial discreet model, which shows the part of exchanger where condensation occurred and the other part where the air is only cooled. Transition between these two modes is then continuous.
Another interest of the discreet approach for modeling is the possibility to build different structures of heat exchangers. The basic cell is a finned tube where air and water (the cooling fluid) are flowing in

counter current. With this cell, it is possible to model a set of exchangers with one or more rows connected in series or in parallel (for the water side).

Icon	**Parameters**
 *Cold battery*	? Dimensions: length, high, thickness, spin number and density, tube diameters, material properties. ? Number of tubes per vertical row ? Number of rows

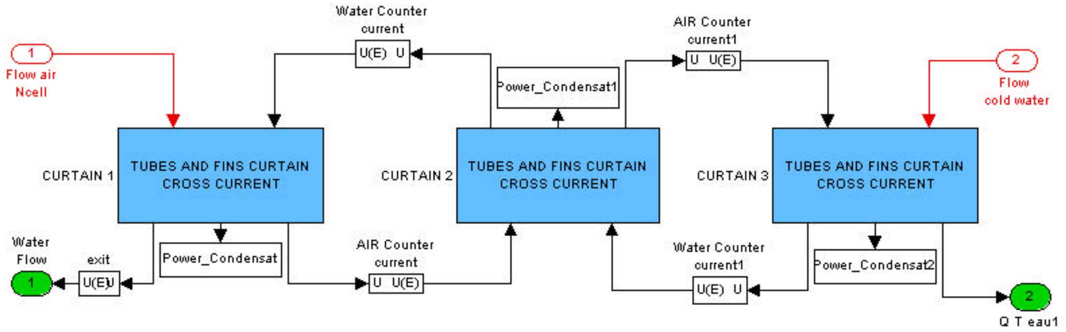
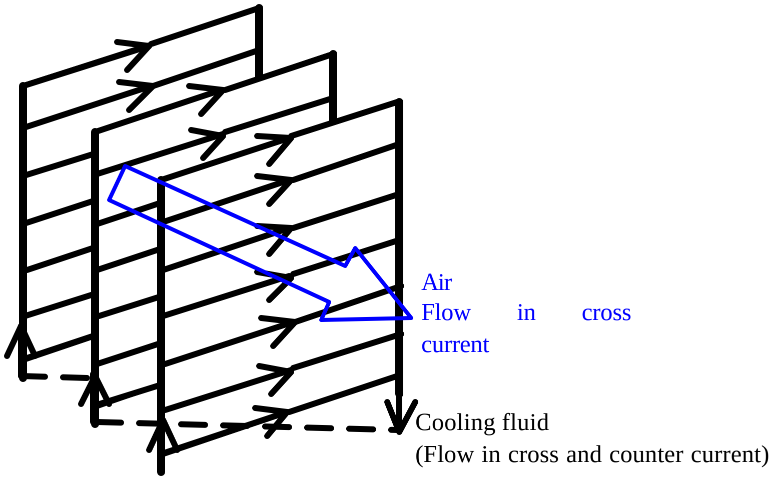


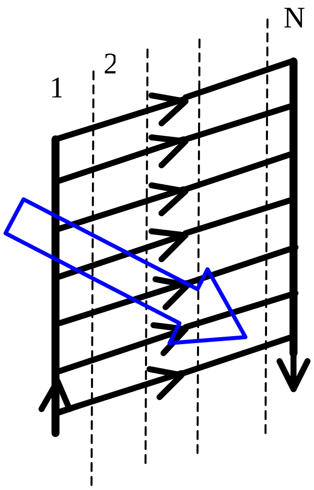
Diagram of the modular conception: three rows in counter flow

Hypothesis:

The exchanger is composed of finned tubes laid out on the parallel surfaces. The air crosses these surfaces perpendicular to the tubes and cools gradually. At each surface, the temperatures of the coolant and air are not uniform and present a space dispersion. To simulate these various temperatures, the exchanger is cut out in cells (see figure).

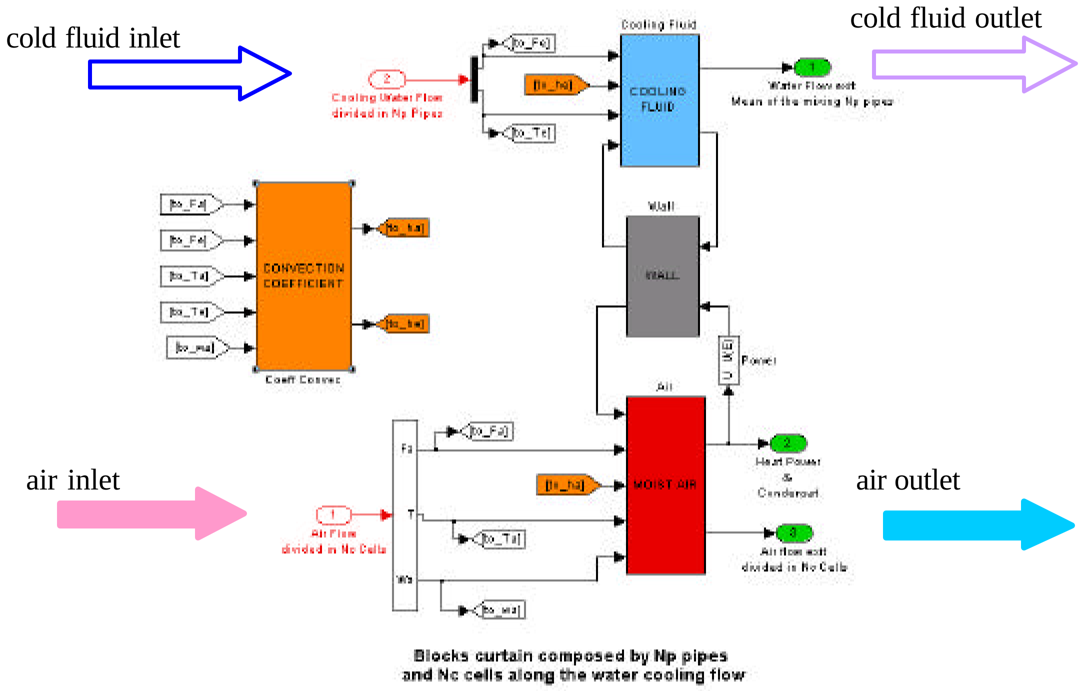


Cold battery (three rows and Np pipes)



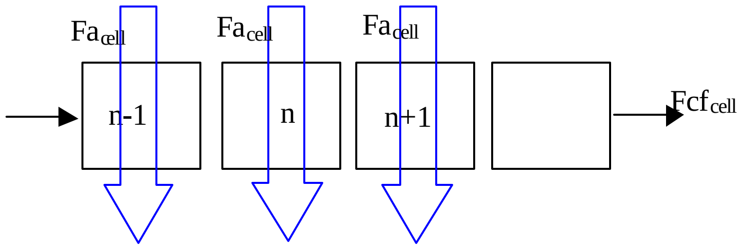
Nc cells decomposition inside one row

Physical equations:
For each cell, the heat transfer between air and water (the supposed cooling fluid) is written with convection and conduction around the exchanger walls. Two correlations are considered for air side taking into account the convection coefficient with or without condensation.



Decomposition of a cell in three blocks where are calculated mass and energy balances

Cells are the basic elements of the exchanger. The dynamic balances of mass and energy describe them. The following figure shows the cells for one pipe of one row.
Air flow is divided in Np * Nc elementary flows, and the cooling fluid is divided in Np flows at the inlet of a row and collected at the outlet before the next one.



Pipe decomposed in cells with cross current flows

Flows:

$$Fa = Fa_{cell} * Np * Nc$$

$$Fcf = Fcf_{cell} * Np$$

Heats exchanged by air and cooling fluid through the wall for the cell "n" are:

$$Pwa_n = h_a * Sa_{cell} * (Tw_n - Ta_n)$$

$$Pwcf_n = h_{cf} * Scf_{cell} * (Tw_n - Tcf_n)$$

Sa_{cell} and Scf_{cell} the heat exchange surfaces for one cell depending on the dimensions of the rows.
for air through finned pipes we use the equation

$$j = St * \Pr^{2/3} = 0.14 * Re^{-0.328} * \left(\frac{ST}{SL}\right)^{-0.5} * \left(\frac{s}{De}\right)^{0.31}$$

$$ha = r * V * Cp * St$$

("Technologie des échangeurs thermiques" Techniques de l'Ingénieur)

The rate exchange increases with the condensation mainly by the term of latent heat and secondary by the change of the thermal resistance. The latent heat term is then calculated but the corrective coefficient of the correlation is omitted.
In fact, no correlations for mass and heat transfer in the case of non condensable mixture are available and we keep the same correlation for both modes. This simplification is a source of errors on the heat power and on the temperature levels but does not change the dynamic behavior and the appearance of the transition. Here, the goal is not to predict the heat exchange with accuracy but to give the main behavior.
For industrial applications, specific experiments will be necessary to set up the correlation. Then, all the coefficients of the equation will have to be identified for the both modes.

for the cooling fluid

$$Nu = 0.023 * Re^{0.8} * \Pr^{0.4}$$

$$Nu = \frac{h_{cf} * Dh}{l}$$

(Colburn)

Energy balance:

for the cold fluid $$M_{cf} * Cp_{cf} * \frac{dTcf_n}{dt} = F_{cl} * (Tcf_{n-1} - Tcf_n) + Pw_{cf}$$

for the wall $$M_W * Cp_W * \frac{dTw_n}{dt} = -Pw_{cf} - Pw_a$$

for the air $$M_a * Cp_a * \frac{dTca_n}{dt} = F_a * (Ta_{in} - Ta_{out}) + P_{cond} + Pw_a$$

$$P_{cond} = -F_a * (wa_{in} - wa_{out}) * Lv$$

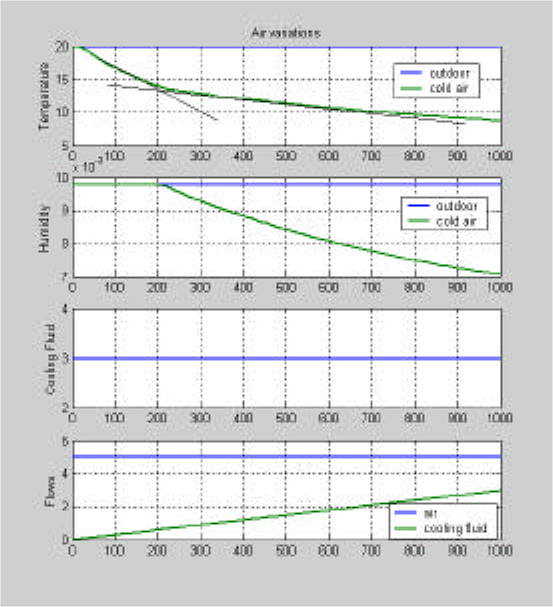
The condensate water:

$$F_{cond} = F_a * (wa_{in} - wa_{out})$$

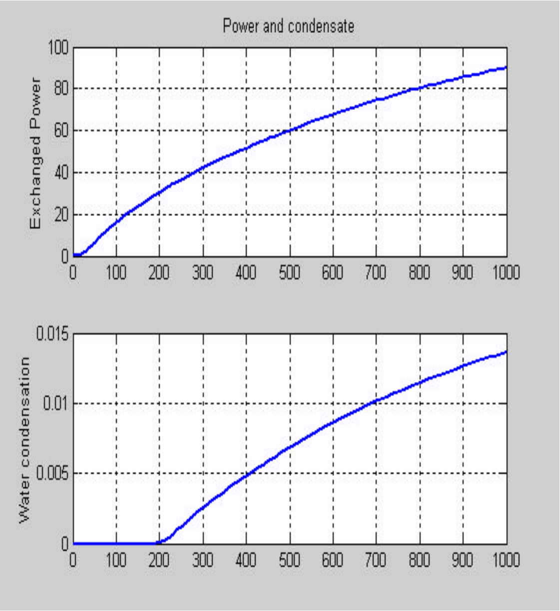
Steady state Simulations

We check with the following simulations that the exchanger has two working modes dry and humid. The mass flow rate of the cooling fluid increases linearly in the simulation in order to increase the heat exchange.

Temperature and humidity change clearly theirs derivatives whereas power increases continuously without break point.



Dry to humid conditions with cooling water changes

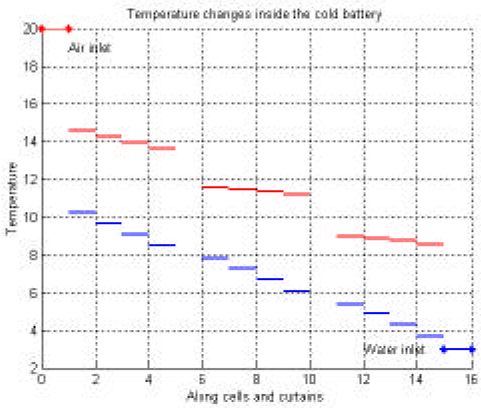


Power and water liquid condensed by cooling

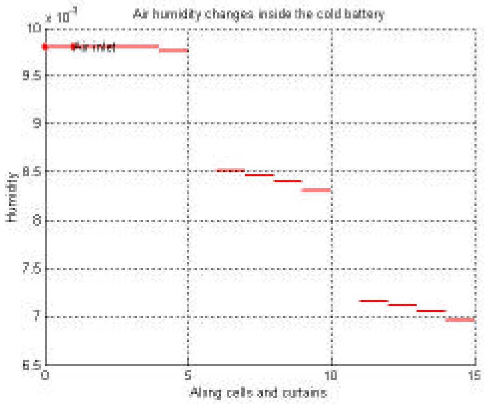
Exchanger precision is chosen by the numbers of cells given a more or continuous aspect. The numbers of rows is attached to the power design.

Following graphs show temperature and humidity variations through the rows and along the tubes of each row.

At the entrance, the air temperature is equal to 20°C in front of the first row and leaves it after cooling at a temperature from 13 to 15 °C. At the same time, temperature water inlet is at about 18°C and the water flow is warmed by the heat exchange with the air flow leaving the row at the fourth cell with a temperature at 10°C.

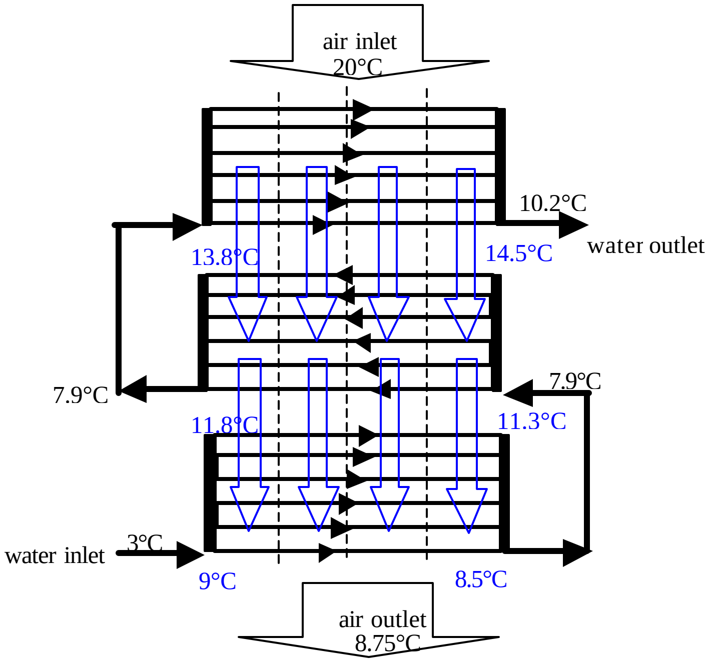


Calculated temperatures inside exchanger for a 4 cells and 3 rows structures



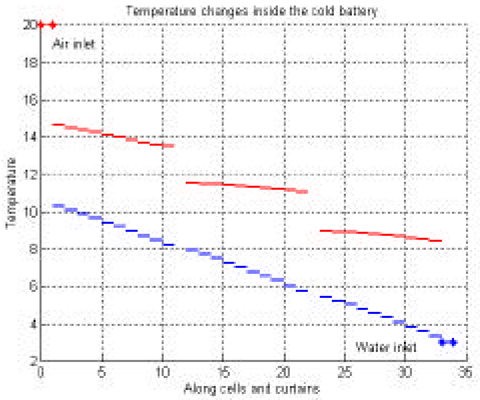
Calculated humidity inside exchanger for a 4 cells and 3 rows structures

The schematic view of this 4 cells x 3 rows exchanger is:

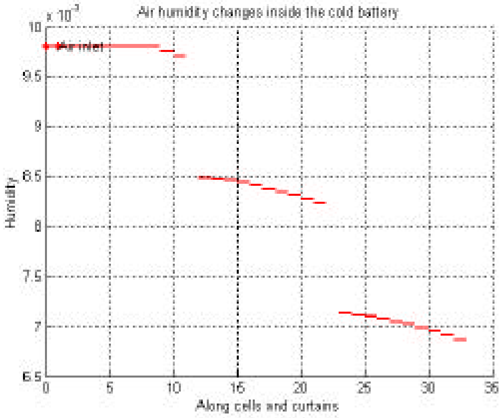


Example of temperature variation inside the cold battery

The same simulation has been made with 10 cells decomposition per row. The precision is better than with the 4 cells decomposition but temperature and humidity are quite the same. For our purpose to simulate the regulation it will be enough to consider only the 4 cells decomposition.



Calculated temperatures inside exchanger for a 10 cells and 3 rows structures

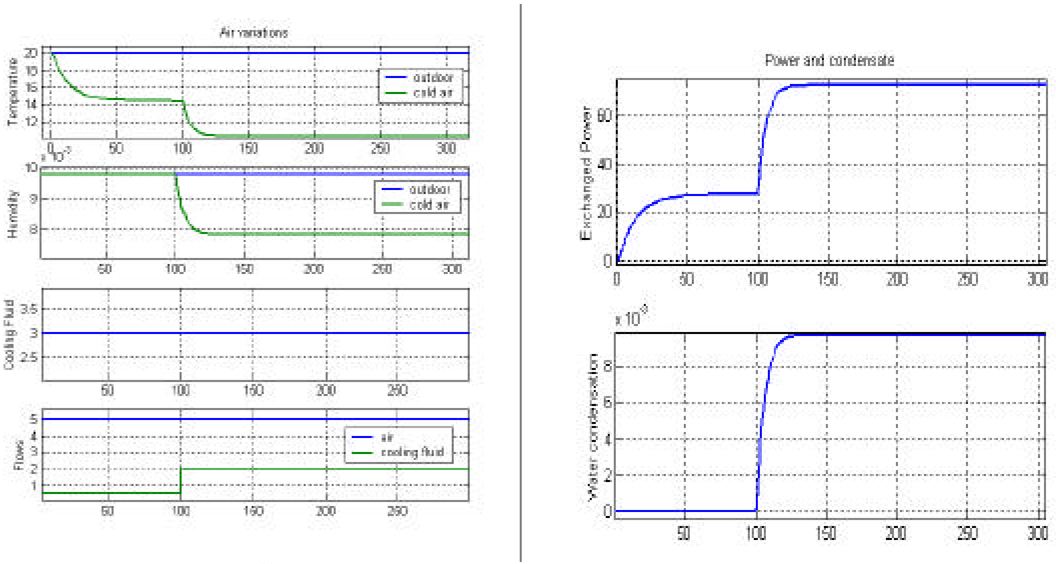


Calculated humidity inside exchanger for a 10 cells and 3 rows structures

Dynamic Simulation

The exchanger model has been described by dynamic equations simulating the inertia of the wall and the fluids. The heat exchanged and the outlet temperatures reached static values after transient phase. Response time of the exchanger is a needed parameter to setup the regulator and can be obtained by simulating changes in the fluid properties. Next figures show the response time for a step on the air flow rate and a step on the cooling fluid flow rate:

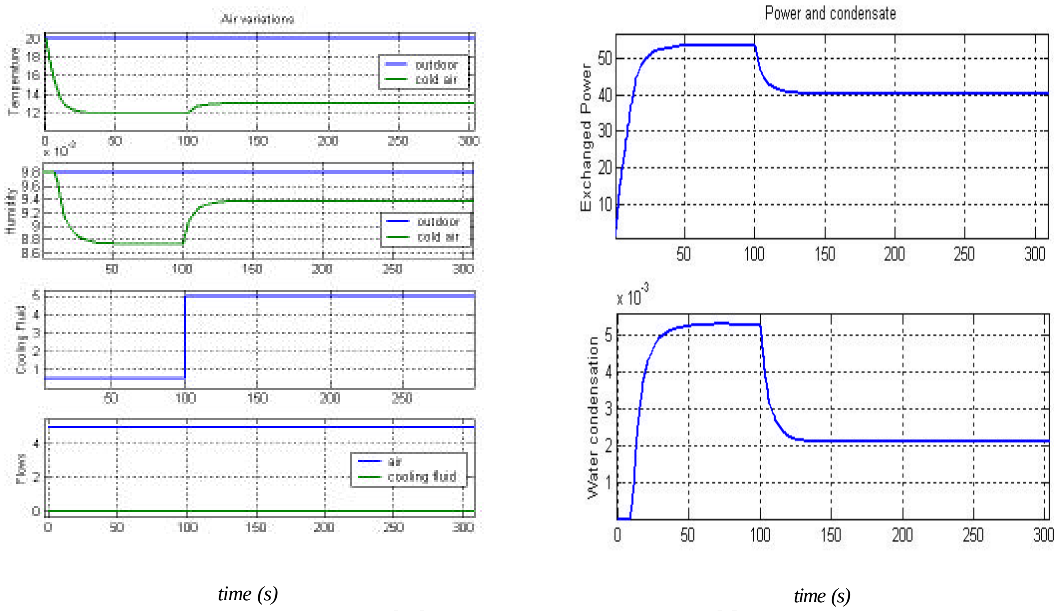
? flow step of the cooling fluid :0.5 to 2 kg/s
? temperature step of the cooling fluid: 0.5 to 5°C



time (s)

time (s)

Dynamic behavior to a cold flow step



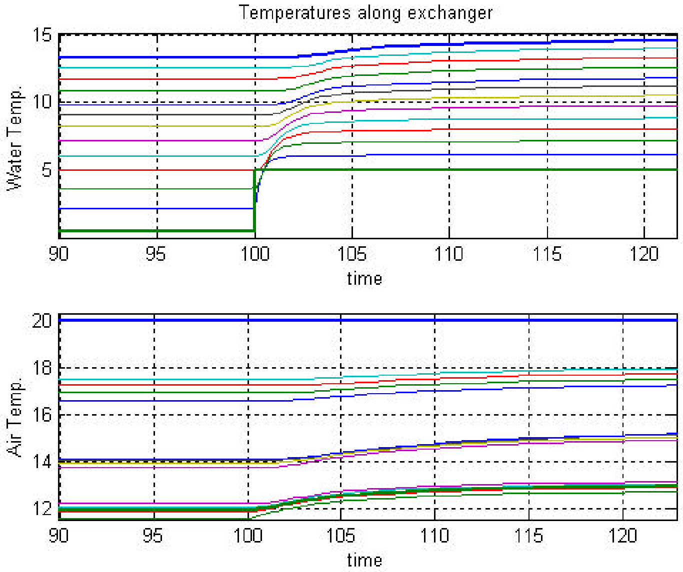
Dynamic behavior to a temperature cold step

The dynamic behavior is a function of the masses (of the wall and of the fluids) and also a function of the transit time of the cooling fluid.

Following simulation compares the time delay and the time-constant of the exchanger after a step of the temperature of the coolant:

? inlet temperature at time< 100 s : 1 °C

? inlet temperature at time > 100s : 5 °C.



Propagation of the temperature front after a step on the water temperature

The time delay (<5 s shown on the figure) due to the propagation of the flow inside the exchanger is negligible in comparison of the time constant due to the inertia (~50 s).

3.2.5 HOT BATTERY

Principle

The hot battery block calculates the heat exchange between air and a warming fluid. The same exchanger model than the cold battery is used. Dimensional features are kept identical. The drying effect never occur because the higher temperature of the warming fluid.
The descriptive equations are the same than those used for the cold battery.

Icon

Hot battery

3.2.6 OUTDOOR AND PERTURBATIONS

These blocks are not blocks describing of the physical parts of the installation. They gather a whole of blocks representing the external parameters influencing the operation of the system of air-conditioning.

3.2.6.1 ATMOSPHERIC AIR

From the data commonly used to characterize the atmospheric state (pressure, temperature, and relative humidity), this block calculates the values of the corresponding effort variables.
For that, we use the Adersa thermal library.

Parameters

The outdoor air is specified by:

? temperature: $T_{outdoor} = constant$
? humidity (relative): $Hr_{outdoor} = constant$
? variation curves of temperature and humidity, for example:

$$Hr_{outdoor} = 45 - 15 * \sin(\frac{p}{7 * 3600})$$

$$T_{outdoor} = 20 - 5 * \sin(\frac{p}{7 * 3600})$$

3.2.6.2 DISTURBANCES

The block "Disturbances” gives all the disturbances on the flow variables: dry air flow, vapor water flow, enthalpy flow, inside power. The exit of this block is thus the vector of the flow variables.

Two kinds of disturbances are tested: vapor income, and heating power. The important point hold in the non measurement of these perturbations.

Parameters

Perturbations:

? vapor mass flow, for example: $Fvapor_{perturb} = 0.002$

? delivered power: $Pw_{perturb} = 10e3 * \sin(\frac{p}{7 * 3600})$

? transfer coefficient of the heat losses by insulation:

$$Pw_{insulation} = K * S_{room} * (T_{outdoor} - T_{room})$$

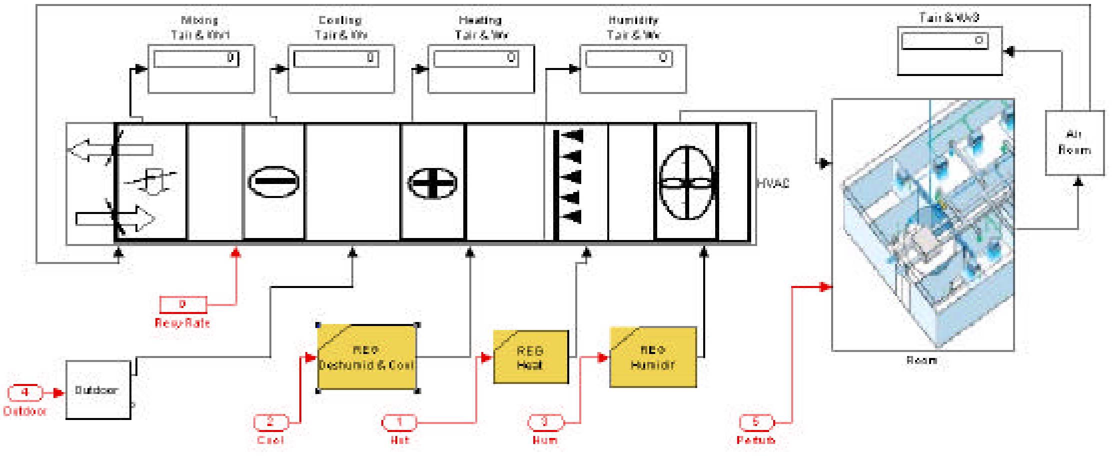
3.3 HVAC MODEL

The fitting of the components make possible to model in a dynamic way several air-conditioning systems.
Once an air-conditioning system built, simulation under Matlab Simulink makes possible to test the regulation under some disturbances.
The possibility of quickly modifying the whole of the parameters allows easier sensitivity studies.

We present in the following paragraph an example of system of air-conditioning under dynamic operation, its response to external disturbances or modifications of points of operation.
The thermal part and the regulator compose the whole process. Three actuators are available to manage temperature and humidity.

The size of the process must be changed (see paragraph above) in order to design the HVAC more or less powerful in comparison to the room volume. It affects the quality of the regulation essentially because the room and HVAC time constants must changed in great scale.

Icon

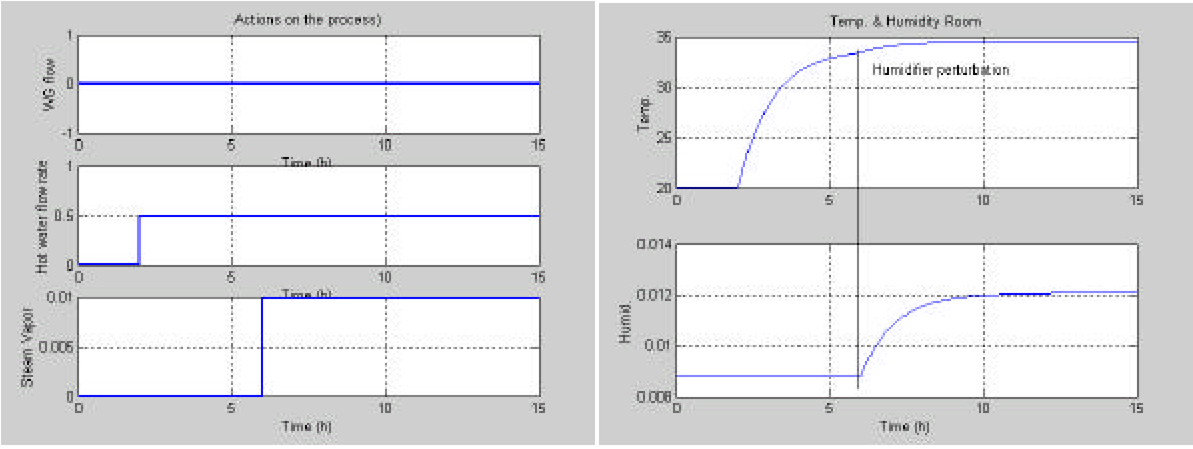


Simulink bloks: HVAC, Room and Regulator inlet ports

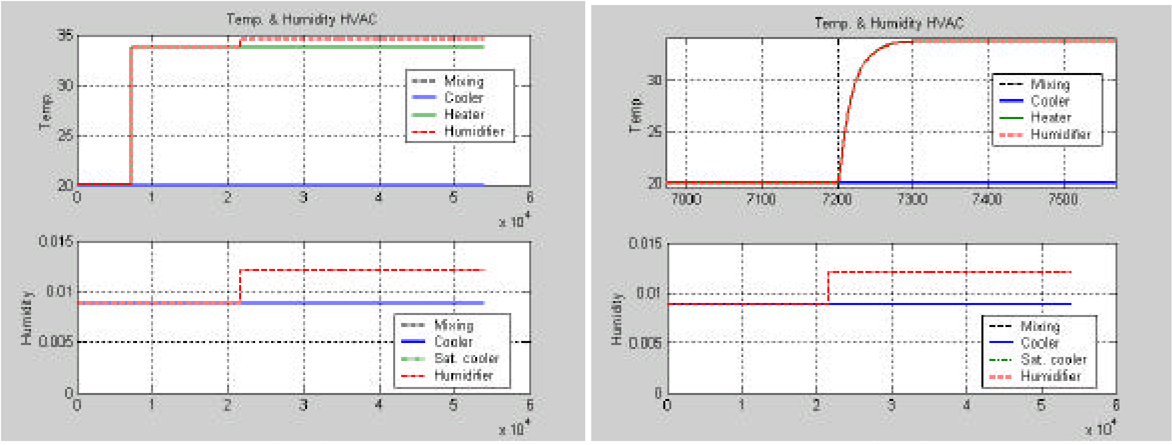
Before to build the regulator, it is important to observe the responses for each manipulated variable to determine response time, time delay, gain, and to quantify perturbations of one action on the others.

Examples of calculated points by specifying the actuator positions (without regulation) are presented on the next figures.

Two steps are applied successively on:
? the heating fluid flow (hot battery action)
? the vapor flow rate (humidifier action)
In this simulation, the air mass flow rate is 9000m^3/h for a 10000m^3 room. The dynamic responses are easy to observe for each action on the HVAC. Left figures show the manipulated variable, the right figures the controlled variables.



Room response to steps of warming heater flow and vapor

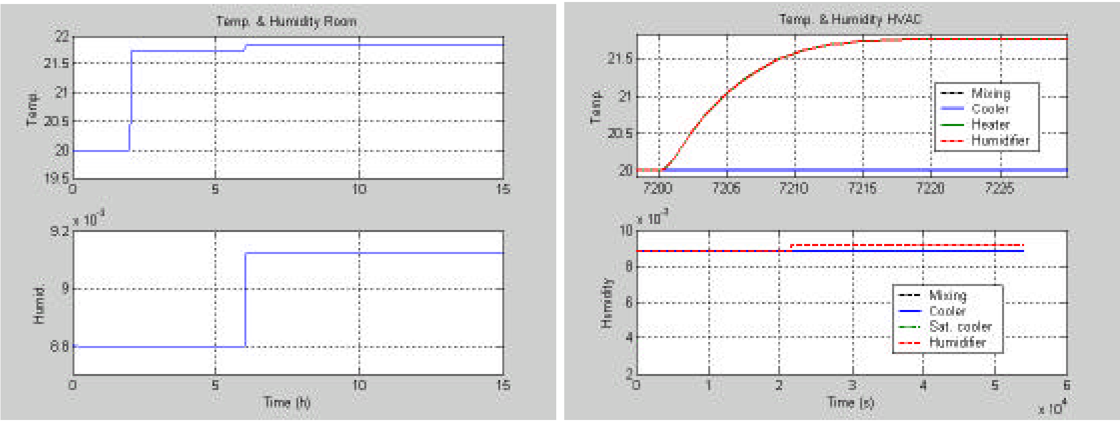


(time s) *(time s)*

The HVAC temperature and humidity

The HVAC dynamic (t ~ 50s) is negligible beside the room one (t ~4000s). We observe that the humidifier raises the temperature of about 1 °C.

The same steps are applied with a different air flow rate, increased by a factor 10. We observe, in the next figures, that the dynamics increase strongly (τ_{room} ~ 400s and τ_{HVAC} ~ 8s) as expected.



Dynamic response for a large air flow before room volume

The operating conditions affect strongly the response time of the process. So, the robustness of the regulation will be solicited by the dependence of the room and the HVAC responses, the gains and the time constants, with the working conditions like the air flow rate and with the perturbations coming from the actuators interactions.

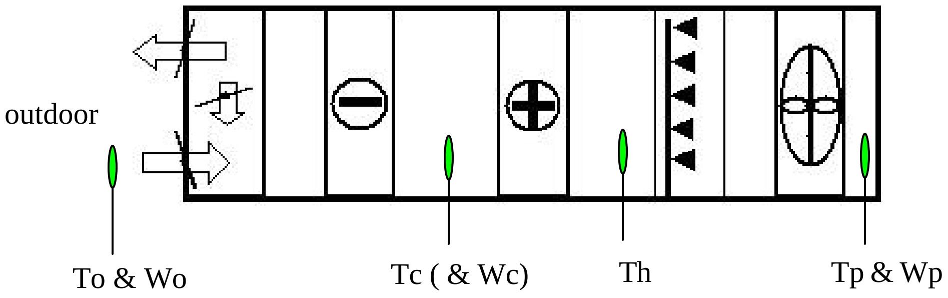
4. REGULATION

The regulation problem in the simplified case needs to control three components to achieve the two set points inside the room. These components and the real acting variables are:
? the cooler by the cold fluid mass flow rate
? the heater by the warm fluid mass flow rate
? the humidifier by the vapor flow rate.

Mixing outdoor and room air allows energy reduction. But outdoor rate is dependent of the application (hospital, building …) and is usually a constraint more than a regulation variable.

Temperature and humidity are the goals of the HVAC system. The humidity measurement is expressed by weight of water per weight of dry air. At the cold battery, air exhaust must be at the saturation point and then humidity is equivalent to the temperature to determine the air state. We use this feature for the regulation.

The HVAC measurement is then the following:



HVAC Air measurements

4.1 STRUCTURE OF THE REGULATION

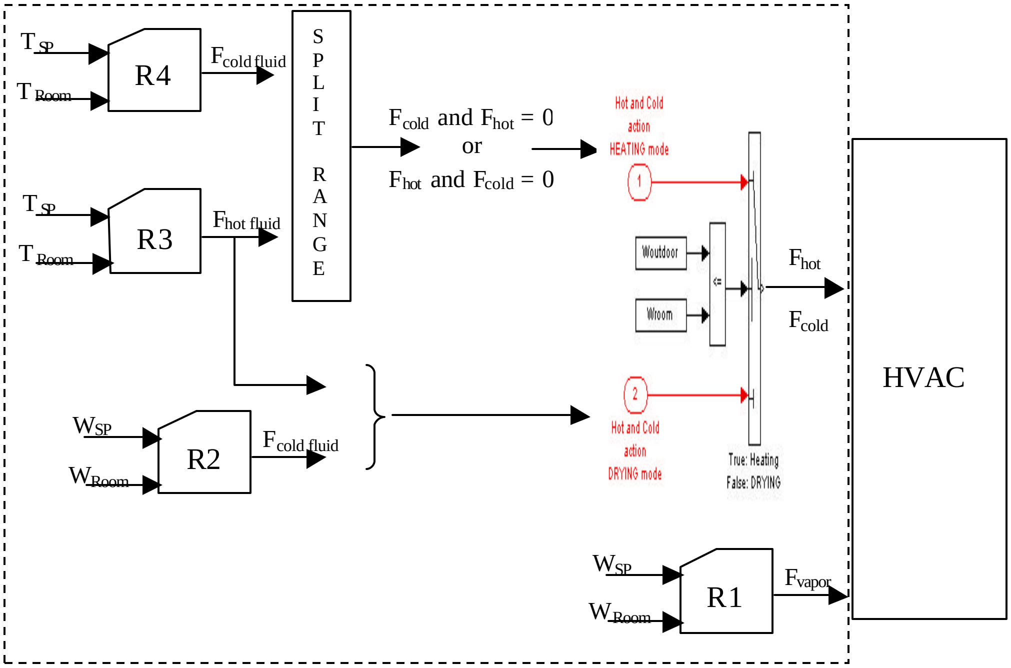
Priority is given to the humidity set point for which the cold battery is used to dry air. The comparison between outdoor humidity and room set point indicates the working mode of the humidifier and the cold battery.
In case where the humidity set point and temperature set point are not compatibles, the regulation choose to achieve the humidity set point (the other choice is valid). Whole possible cases are shown in the table.

actions	$W_{outdoor} > W_{SP}$	$W_{outdoor} < W_{SP}$
$T_{outdoor} > T_{SP}$	? cooling for drying	? cooling ? humidifying
$T_{outdoor} < T_{SP}$	? cooling for drying ? heating	? heating ? humidifying

4.1.1 ONE LEVEL REGULATION

The first proposed regulation has four elementary regulators for the two set points:

? R1 humidifier regulator set by W_{SP} and W_{room}
? R2 cold battery regulator set by W_{SP} and W_{room}
? R3 hot battery regulator set by T_{SP} and T_{room}
? R4 cold battery regulator set by T_{SP} and T_{room}



Global regulation for HVAC and Room seen as only one process

The block Split Range avoids batteries to work together in a less effective way. A logic comparison based on humidity drives the hot and cold actions.

4.1.2 TWO LEVEL REGULATION

The second strategy separates the HVAC and the room by using intermediate set points at the outlet of the air treatment process: Tp and Wp (see "HVAC Air measurements" figure). By this way we control the two parts independently. The regulator as the following structure:

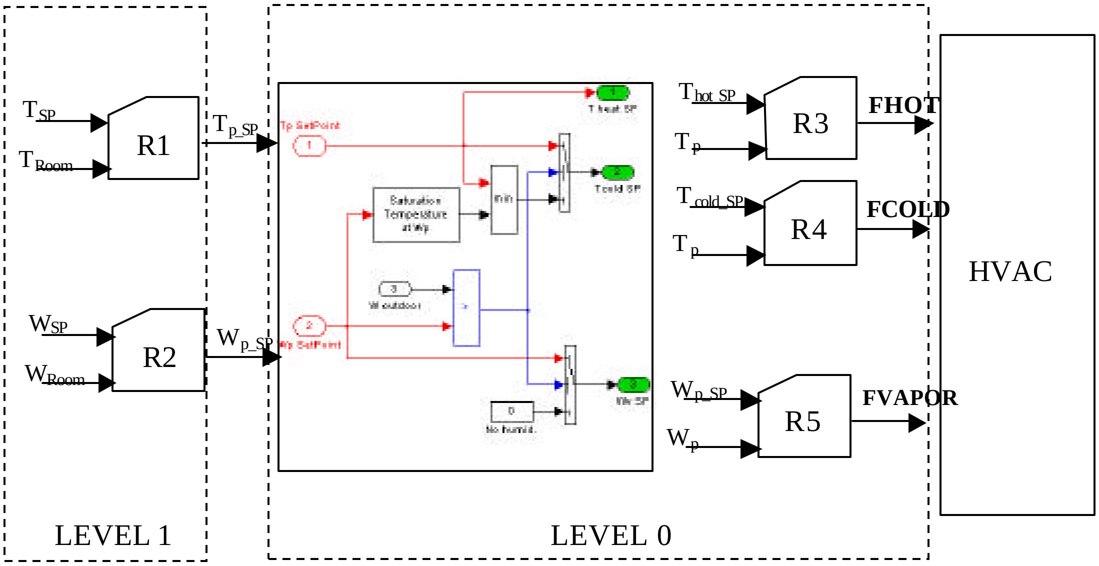
Room

? R1 room temperature regulator set by T_{room} and T_{SP}, calculates T_{p_SP}
? R2 room humidity regulator set by W_{room} and W_{SP}, calculates W_{p_SP}

HVAC

? R3 HVAC temperature regulator set by T_p and T_{p_SP}, calculates F_{hot}
? R4 HVAC temperature humidity regulator set by T_p, T_{p_SP}, W_p and W_{p_SP} calculates F_{cold}

- ? R5 HVAC humidity regulator set by W_p and W_{p_SP}, calculates F_{vapor}



Regulation with two levels dividing the system in the HVAC and room

A logic block calculates the saturation temperature needed to reach the humidity at the cold battery exhaust and gives a new temperature set point equivalent to the humidity. The comparison between outdoor conditions and set points drives the choice for the three set points of the Level 0 regulators.

4.2 REGULATOR

The called regulators Ri (i =1 to 5) in the previous paragraph are regulators based on mathematical models specifying process relations between inlets and outlets variables. Models are more or less complex following the knowledge of the process, the need of accuracy and the calculating power of the regulator.

For this simplified approach of the HVAC, we used first order models to predict the process behavior. Predictive regulators are preprogrammed blocks coming from Adersa's library. All the models are written like:

$$mes = \frac{k * e^{\Theta * p}}{t * p + 1} mv$$

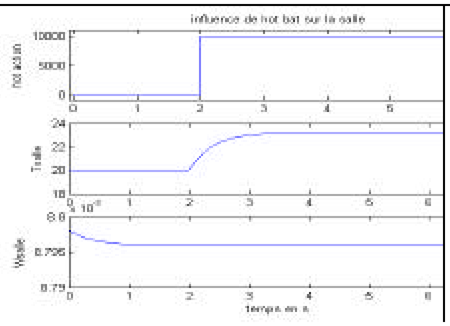
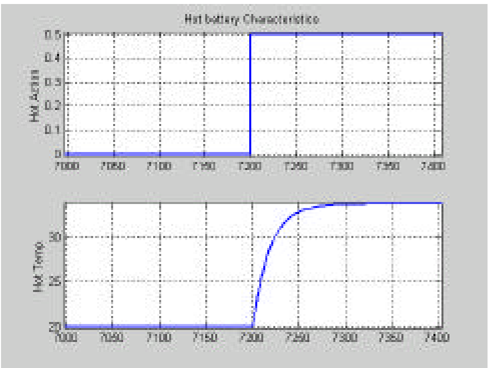
This kind of regulator allows to take into account constraints on the manipulated variable and tendencies due to the perturbations.

4.2.1 DETERMINATION OF REGULATOR PARAMETERS IN OPEN LOOP

Regulator parameters are determined in exciting the components of the control system. So, in applying a signal on a manipulated variable, we evaluated the room response in temperature and humidity. This response characterizes three variables: the gain, the time constant and delay of the system.
The following examples are given for the two strategies.

4.2.1.1 HEATER MODEL

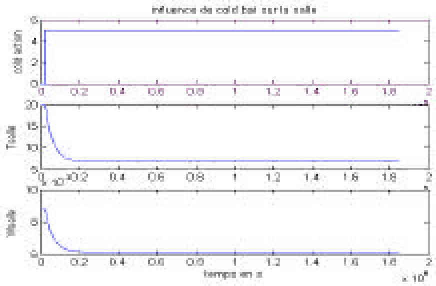
Here, we evaluated the influence of the hot battery on the thermal heat in the room. It's important to note that the control variable of this component is represented by a heat power. So, the regulator's parameters are determined for a signal of 10000 W. The response and the regulator concerned parameters are represented in the diagram. It's easy to note that for this case, the system response is of thermal nature only.

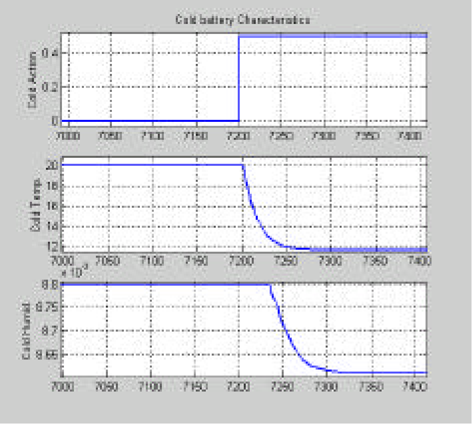
<table>
<tr><th colspan="2">One level strategy</th></tr>
<tr><td>? 
</td><td>? gain = 3e-4 K/ (kg/s)
? time constant = 4000 s
? time delay = 0 s</td></tr>
<tr><th colspan="2">Two levels strategy</th></tr>
<tr><td>

time (s)</td><td>Values obtained for F_{hot} = 0.5 kg/s and Fair = 3 kg/s
? gain = 27.4 K/ (kg/s)
? time constant = 50 s
? time delay = 0 s</td></tr>
</table>

4.2.1.2 COOLER

As above, we evaluate the cold battery regulator parameters in applying a constant signal on the control variable. This last is represented by the water flow entering at a cold temperature. The room changes its temperature and its humidity that the following diagram shows. So, the regulator parameters are double depending on whether we want to control the temperature with a constant humidity (cooler without condensation) or to control the humidity implying the variation of the temperature on the saturation line. The values of the gain, the constant time and the delay are given.

<table>
<tr><th colspan="2">One level strategy</th></tr>
<tr><td>


</td><td>
Temperature response
? gain = -0.54e-3 K/ (kg/s)
? time constant = 4000 s
? time delay = 0 s
</td></tr>
<tr><th colspan="2">Two levels strategy</th></tr>
<tr><td>


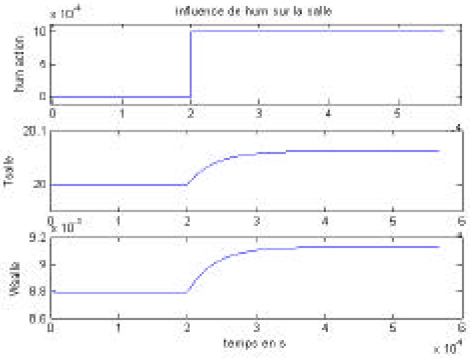
time (s)
</td><td>
Values obtained for F_{cold} = 0.5 kg/s and Fair = 3 kg/s

Temperature
? gain = -16 K/ (kg/s)
? time constant = 50 s
? time delay = 0 s
Humidity
? gain = 1e-4 $(kg/s)^{-1}$
? time constant = 50 s
? time delay = 0 s
</td></tr>
</table>

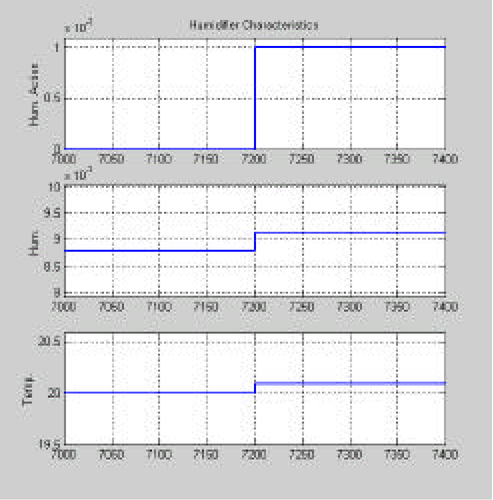
4.2.1.3 HUMIDIFIER

The control variable of this component is characterized by a flow of vapor. So, in applying a constant signal, we determine the humidifier regulator parameters. The room response is of two types because the addition of humidity implies variation of the temperature.

So, we keep two types of parameters who represent the impact of this control variable on the temperature and the humidity in the room. These two responses with the parameter values are represented in these following tables.

<table>
<tr><th colspan="2">One level strategy</th></tr>
<tr><td>


</td><td>
? gain = 0.33 $(kg/s)^{-1}$
? time constant = 4000 s
? time delay = 0 s
</td></tr>
</table>

<table>
<tr><th colspan="2">Two levels strategy</th></tr>
<tr><td>

time (s)</td>
<td>Values obtained for F_{vapor} = 1e-3 kg/s and Fair = 3 kg/s

Humidity
? gain = 0.33 $(kg/s)^{-1}$
? static model
? time delay = 0 s
Temperature
? gain = 800 K/ (kg/s)
? static model
? time delay = 0 s</td></tr>
</table>

4.2.1.4 REMARKS

The room dynamics is equal to 4000 s, those of the HVAC are around 50 s and then can be neglected for the first strategy.

The Cooler is describes by a temperature model and a humidity model for condensation. Humidifier has a temperature model for perturbation tendency.

First order models are satisfactory for common regulation but may be improved especially to take into account gain variation with flows and temperature level. As we know exchanged power is driven by the temperature difference between air and cooling or heating fluids and is also a function of the heat transfer coefficient so that the gain must be written with these terms.

Non linearity appears with the condensation so that the cooler model must be inaccurate for special applications. Solution is given by same regulator but with a more detailed model.

4.3 DISTURBANCES

Disturbances coming from the outside and inside activities are usually non measured. The regulation must make up for by a quick response. But process itself is a source of perturbations between its different components. The next table shows some of these interactions.

Actions	**Tendency**	**Perturbed components**
humidifying	increase the temperature	heater and cooler
drying	decrease the temperature	heater
heating	increase the temperature	cooler
cooling	decrease humidity	humidifier

The heater, for example, works alternately or together with the cooler for some cases. Switch on and off and inertia of the exchangers produce small perturbations by heat transfer. Such perturbations can be model and effects compensated by an adding feed forward block at the regulator.

5. SIMULATION EXAMPLES

The following paragraphs show results obtained with the two level regulation.

5.1 SET POINT VARIATIONS

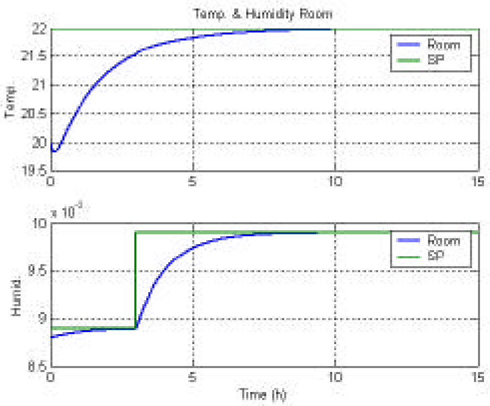
The temperature and humidity changes show the actions of the regulator. Effects of the "closed loop response time" (note t_{CL}) and disturbances models are highlighted.

Next figures show the effect on the dynamic response for a step of the humidity set point when the t_{CL} is reduced. t_{CL} is the main parameter to set up the regulation.

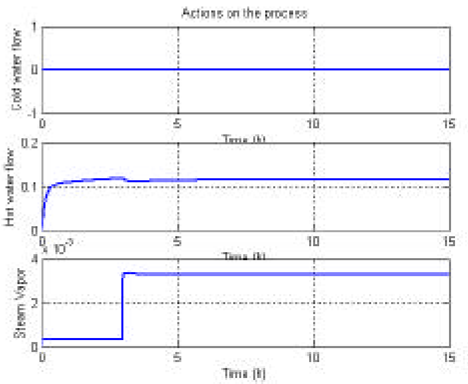
? Simulation conditions:

V_{room} = 10000 m^3
F_{air} = 1kg/s
Outdoor conditions: T = 17°C, Wa = $8.8.10^{-3}$ kg/kg
Temperature set point = 22 °C
Humidity set point = $8.9.10^{-3}$ to $9.9.10^{-3}$ kg/kg

The temperature regulator (R_1) is set up with t_{CL} ~ 400mn
The humidity regulator (R_2) is set up with t_{CL} ~ 200mn

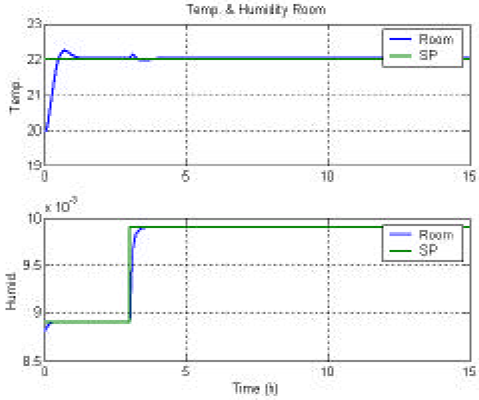


Temperature and humidity changes

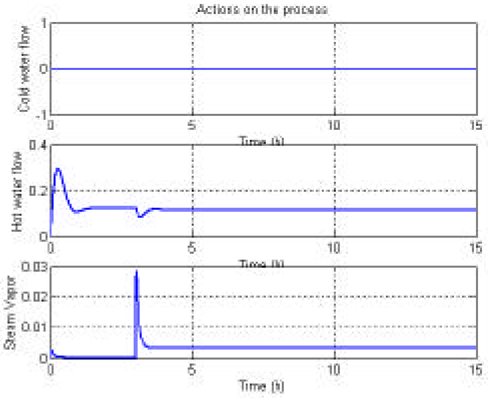


Actions of the regulator

The temperature regulator (R_1) is set up with t_{CL} ~ 40mn
The humidity regulator (R_2) is set up with t_{CL} ~ 20mn



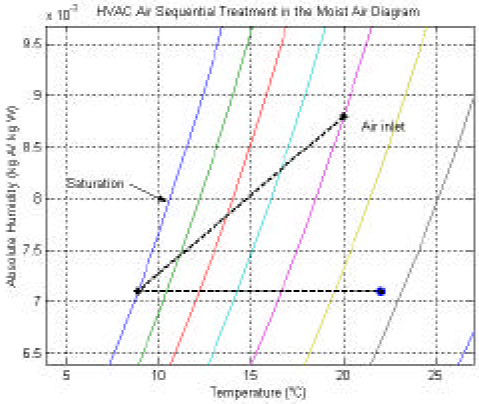
Closed loop response time are divided by 10 for a swift convergence



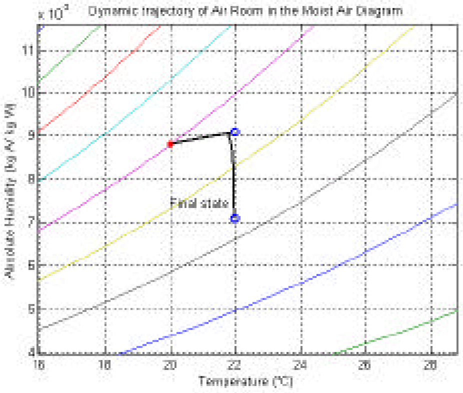
Actions of the regulator

When the t_{CL} is reduced, the set points are reached more quickly (see left figures) and the actuators move more quickly (see right figures). This parameter has to be chosen in respect to the actuators limitations, the response time of the room and the robustness of the regulator for different working situations.

Next figures show the air state on the psychometric chart for the same set points. We see the air treatment by the HVAC system for the final state and the variation of air quality inside the room.



Air state through HVAC system for a steady state



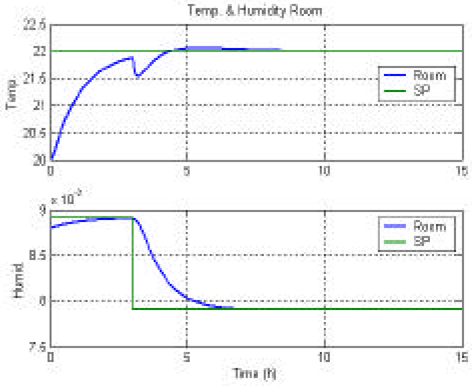
Dynamic trajectory of air room reaching two set points successively

Perturbations have an impact on the air quality during the transient phases. It is possible, if they are measured, to reduce their effects by a model of perturbations. For example, the humidifier changes the temperature as shown on the first following figures and this perturbation can be partially compensated as shown on the second one.

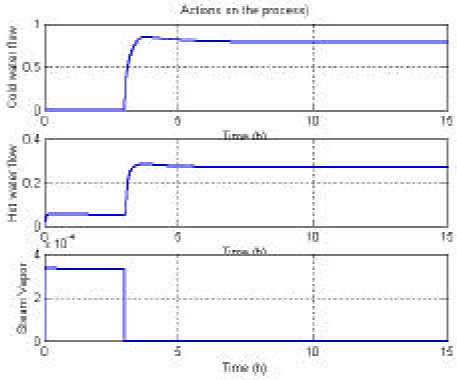
? Simulation conditions:

F_{air} = 1kg/s

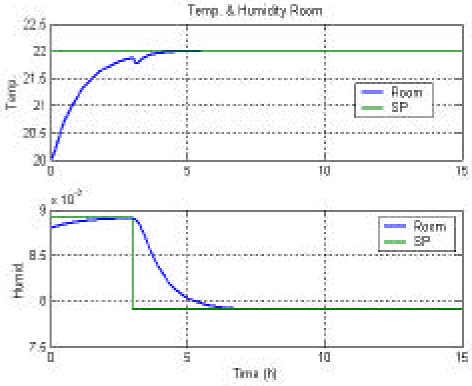
Outdoor conditions: T = 17°C, Wa = $8.8.10^{-3}$ kg/kg
Temperature set point = 22 °C
Humidity set point = $8.9.10^{-3}$ to $7.9.10^{-3}$ kg/kg



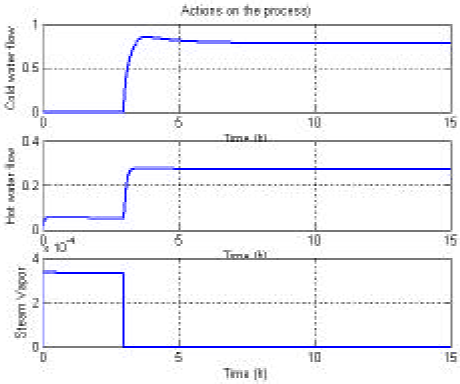
Drying as a perturbation of the temperature



Actions of the regulator



Drying as a perturbation of the t emperature whose effect is taken into account by the temperature regulator



Actions of the regulator

When the humidity step occurred, the temperature is decreased of about 0.5°C. With the perturbation model the temperature fall is of 0.1°C.
For all the measured perturbations (on the HVAC process as well inside the room), a compensation can be realised by the regulator to diminish their effect on the controlled variables.

5.2 OPTIMAL TRAJECTORY

Possibility to manage air state improved the total consumption of the HVAC system. It is especially true if we compare a HVAC where the drying effect is non well controlled by the cooling battery. This kind of system drives the humidity of air at a minimum value and adapts it by the humidifier whose control is easier.

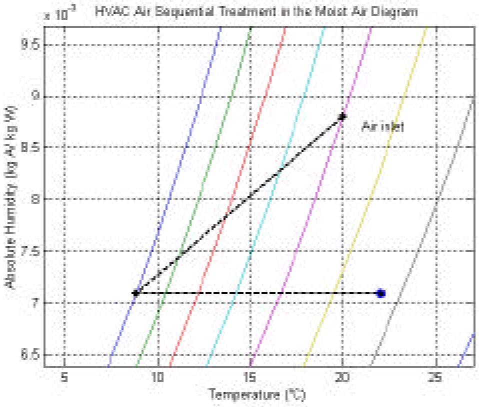
The next two simulations show the gain obtained:
? humidity set point is managed by the cooler
? humidity is raised to the minimum value at the cooler then managed by the humidifier.

The next figures show the air states into the HVAC process and into the room.

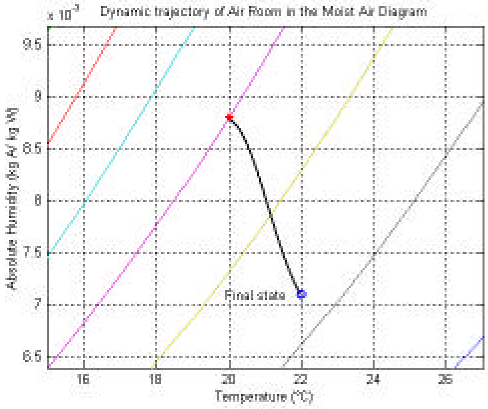
First simulation (see white figures) assumes that the regulator is able to reach the humidity set point by cooling the air at the saturation point. The state of the room changes without opposite evolutions of the temperature and of the humidity which decrease continuously.
In the second simulation, the cooler operates to dry the air at a minimum value of the humidity always under the set point (see gray figures).

Simulation conditions:

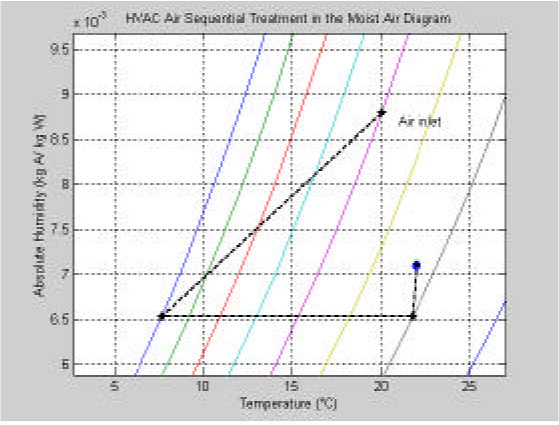
V_{room} = 10000 m3
F_{air} = 3 kg/s
Outdoor conditions: T = 20°C, Wa = $8.8.10^{-3}$ kg/kg
Temperature set point = 22 °C
Humidity set point = $7.1.10^{-3}$ kg/kg
Cooling flow rate = 3 kg/s for the second simulation (controlled for the first simulation)



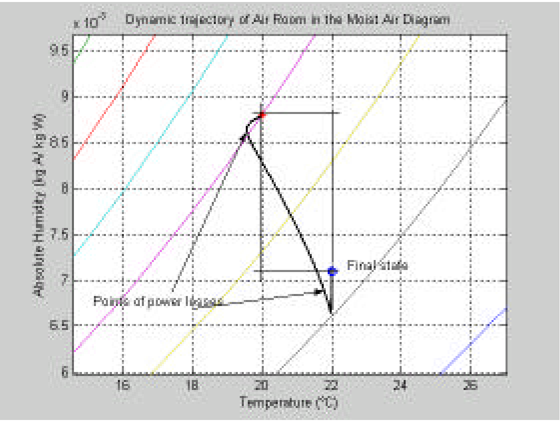
The cooler reaches the humidity set point



Direct trajectory obtained without opposite actions

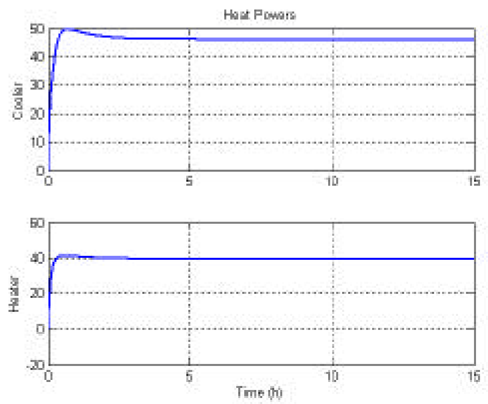


Drying is set at the maximal value of the exchanger capability

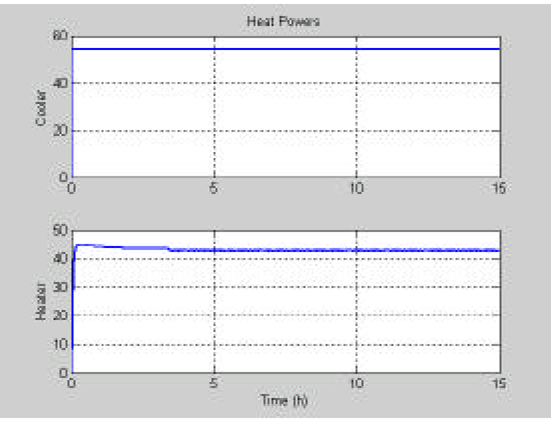


Trajectory is non optimal

The comparison of the consumption shows the interest to control with accuracy the set point.



Power consumptions
46 kW Cooler, 40 kW Heater
Vapor consumption: unused



Power consumptions
54 kW Cooler, 42.5 kW Heater
Vapor consumption around 7 kg/h

Drying operation needs a great amount of power and the way to minimise the consumption is to control the humidity at the outlet of the cooler.

Some systems work by drying more than necessary to avoid a precision adjustment of the regulation. For these cases optimisation is possible. For such systems, the consumption power can be reduced by a new regulator of the humidity.

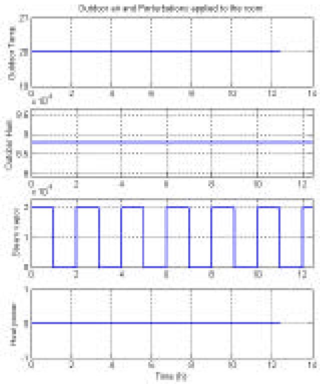
5.3 PERTURBATIONS INSIDE THE ROOM

Some disturbances inside the room modify the temperature and - or humidity that the regulator must compensate. The major difficulty is unpredictable (non measured) character of these disturbances.

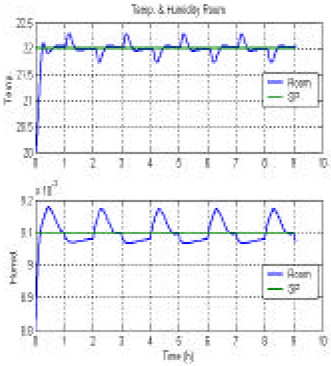
First simulation is done assuming a production of vapor by a process inside the room. The water vapor modifies the room humidity and the regulator of the HVAC tries to compensate. Its response is adjusted by the t_{CL} to obtain the smallest drifts.

Simulation conditions:

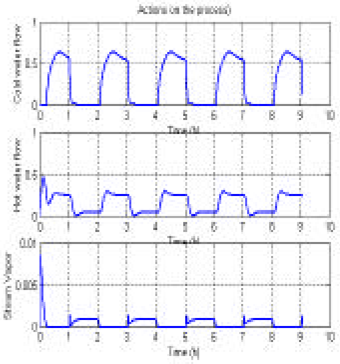
V_{room} = 10000 m3
F_{air} = 3 kg/s
Outdoor conditions: T = 20°C, Wa = $8.8.10^{-3}$ kg/kg
Temperature set point = 22 °C
Humidity set point = $9.1.10^{-3}$ kg/kg



Flow vapor perturbations inside the room



Humity and room temperature



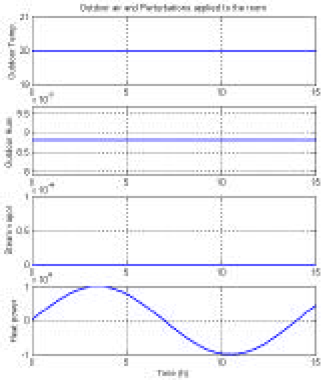
Actions of the regulator

The temperature is close to the set point with a shift of less 0.5°C. The air moisture varies of $0.05.10^{-3}$ kg/kg around the set point what is small variation if we consider that without regulator the end value would be of $10.8.10^{-3}$ kg/kg.

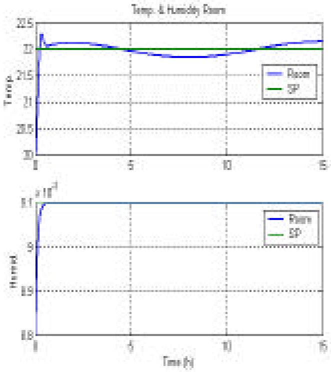
In the second simulation, one supposes that a heat is produced inside the room. The humidity does not change but a small variation in the temperature is observed (see following figures).

Simulation conditions:

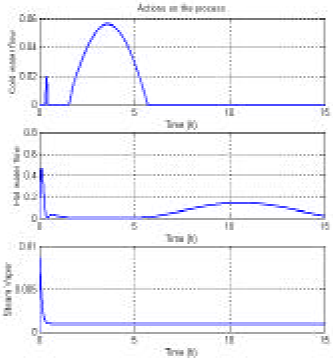
V_{room} = 10000 m3
F_{air} = 3kg/s
Outdoor conditions: T = 20°C, Wa = $8.8.10^{-3}$ kg/kg
Temperature set point = 22 °C
Humidity set point = $9.1.10^{-3}$ kg/kg
Heat delivered inside the room Pw = 0 to 10 kW



Warming and cooling power delivered inside the room



Humity and temperature room



Actions of the regulator

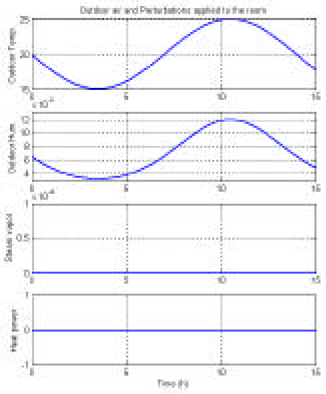
The perturbations tested in this paragraph influence directly the controlled variables inside the room. The regulator acts only when these values change from the set points. In order to limit the shift it is necessary to modify the t_{CL} (here the value is set to 1000 s for both regulator R1 and R2) so that a quick action of the HVAC is obtained.

5.4 OUTDOOR CHANGES

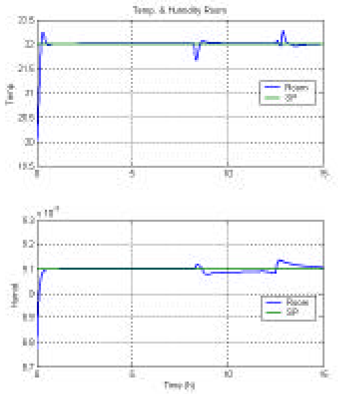
The outdoor conditions change slowly during the day and are a source of disturbances. Usually HVAC are equipped with outdoor captors and it would be possible to use a standard model to predict room disturbances. Such model would be added to the regulator as perturbation model.
Here we observe the outdoor influence at the inlet of the HVAC system. The perturbation is not predicted and the regulator must be self-adaptive to compensate quickly the changes.

Simulation conditions:

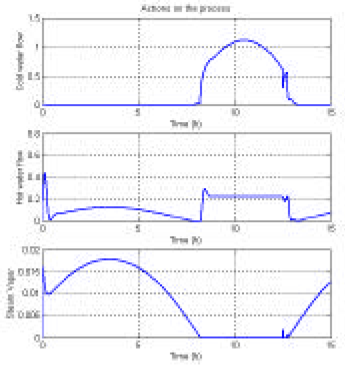
V_{room} = 10000 m3
F_{air} = 3 kg/s
Outdoor conditions: T = 20°C, Wa = $8.8.10^{-3}$ kg/kg
Temperature set point = 15 °C to 25 °C
Humidity set point = 3.10^{-3} to 12.10^{-3} kg/kg
Heat delivered inside the room Pw = 0 to 10 kW



Changes of outdoor temperature and humidity



Humity and temperature room



Actions of the regulator

The regulator controls the humidity and the temperature easily because the variations of the outdoor conditions are slow. It is only when the operating mode (from drying to humidification) of HVAC system changes that the difference between the set points and the values of the room are visible.
The regulator may be considered as efficient.

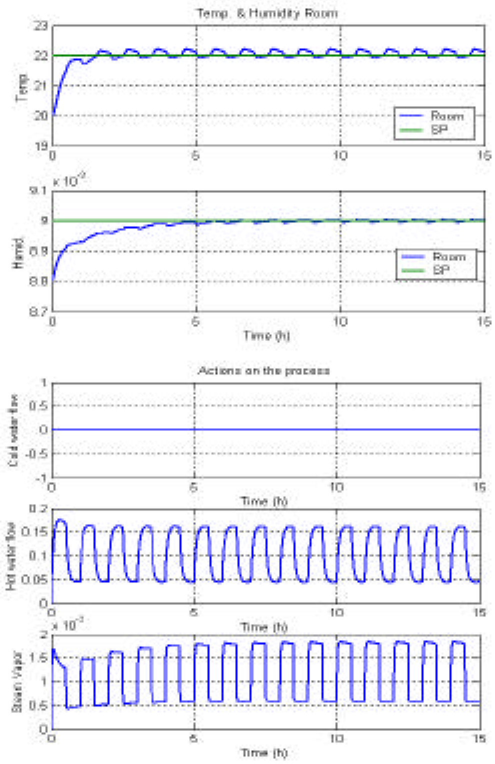
5.5 AIR FLOW PERTURBATIONS

The changes of air flow creates a disturbance owing to the fact that the models used by the regulators are made less accurate. It is then possible to use models with a variable gain depending on the air flow. The next figures show the difference between the constant model (on left figure) and the variable model (on the right figure).

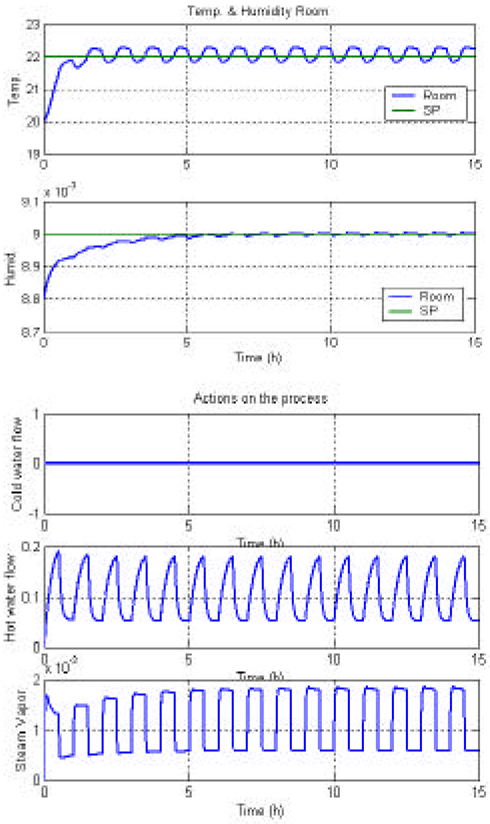
Simulation conditions:

V_{room} = 10000 m3
F_{air} = steps from 3 kg/s to 9 kg/s
Outdoor conditions: T = 20°C, Wa = $8.8.10^{-3}$ kg/kg
Temperature set point = 22 °C
Humidity set point = 9.10^{-3} kg/kg

Regulator with variable gain models



Regulator with constant model



The comparison shows that the temperature shift on the left figure is less important than on the right ones.

When we model the gains of the exchangers with the flow rate, the regulator has a better performance.

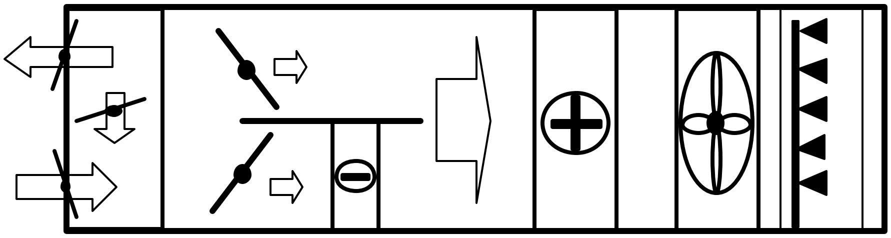
More generally, improvements are expected with accurate models especially when the system is working in a large range of climatic conditions.

6. INTEGRATED DESIGN

The two regulation strategies are possible with more or less captors and first level regulators. But other designs of HVAC are equally possible with other constraints. Furthermore, the thermal sources used for heating and cooling the batteries are at this time outside the air conditioning system. But to realise the best performances it will be interesting to realise the whole apparatus for optimisation.

6.1 POWER OPTIMISATION

Energy losses come partially from a non appropriate control of the HVAC as shown roughly in the previous paragraph. But design itself can be improved. For example, for high drying application, the figure shows a partial drying effect applied to a part of air flow.



HVAC with a split flow for partial drying

Strategy is to dry strongly a part of the air flow so that the mixing flow after the cold battery reaches the set point. Regulation acts by the shutters splitting the flow whereas a constant cooling fluid feeds cold battery. Temperature level must be low enough to dry but higher the freezing point. More accurate is the regulation, more the temperature can be close to 0°C.

Some gain are expected:

? the cooling amount decreases with the flow rate

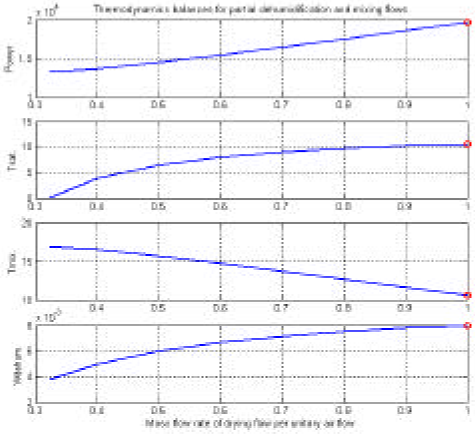
? the heating power decreases with the flow rate

? exchanger sizes are reducing.

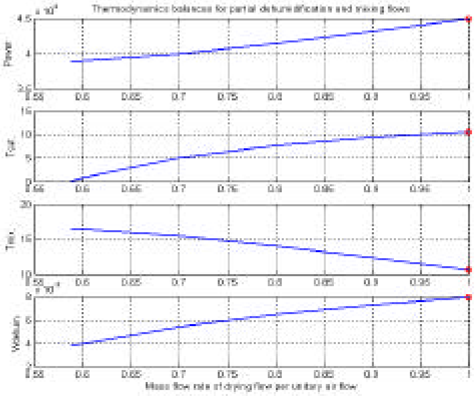
The next figures show two simulations where the outdoor conditions are different and for which the power consumption is calculated. When all the air flow goes through the cold battery the HVAC system is the same than in previous paragraph.

Simulation conditions:

V_{room} = 10000 m3
F_{air} = steps from 3 kg/s
Outdoor conditions: [T = 25°C, Wa = 10.10^{-3} kg/kg]$_{left}$
and [T = 40°C, Wa = 14.10^{-3} kg/kg]$_{right}$
Temperature set point = 16 °C
Humidity set point = 8.10^{-3} kg/kg



Initial state point : 50% Hr , 25°C
Final state point : 40% Hr , 25 °C
33 % cooling power saved
[7 kW /air flow rate] heating power saved (possible)

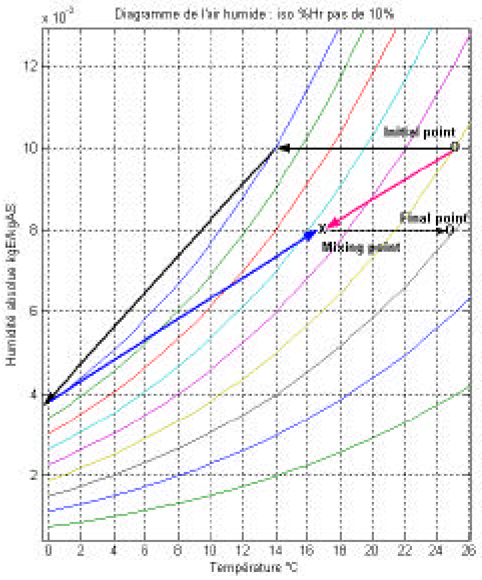


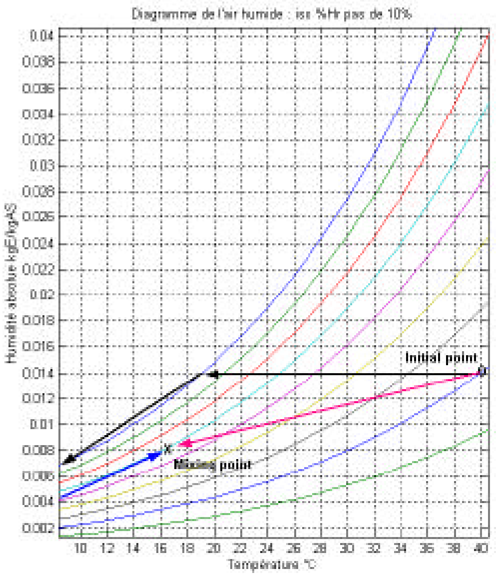
Initial state point : 35% Hr , 40°C
Final state point : 40% Hr , 40 °C
13 % cooling power saved
[6 kW /air flow] heating power possible saved

Figures show the cooling power in case where total flow is dried (red round) and case where only a part of the flow is dried (blue curve). In these special cases, the power consumption is reduced. With such a design, an optimal model based controller should be able to find the best operating condition.

The following chart shows the steps of the air treatment by the HVAC system when the air flow is splitting.

Air way in the psychometric chart





6.2 EXCHANGER STRUCTURE

As described in the component paragraph, exchanger is usually tube rows where air flow is cooled gradually. Thus, by arrangement of the tubes and the flows direction it is possible to create a temperature gradient into the air flow.
Partial condensation may be mastered to achieve humidity set point with a heterogeneous composition to avoid a total cooling to the saturation point. The expected gain is the same than with a split air flow.

6.3 HEAT SOURCES AND AIR CONDITIONING PROCESS

The HVAC system needs a cooling and heating systems. A refrigerating process (using a condensed vapor cycle) composes the cooling one. This process associated or not with a coolant fluid (blend of water and glycol) has its own regulation based on a temperature change of its fluid. The mass flow rate of the refrigerant, which drives the cooling power, is controlled by the start of one or several compressors or by the speed variation of a compressor. But the temperature level, which has a great influence on the heat transfer, changes with operating conditions. Its affects the compressor consumption by the Carnot coefficient. Thus the optimisation procedure includes temperature and flow rate of the refrigerant, the air state points and the structure of exchanger.

We think that a control taking into account whole systems would have better possibilities to improve the whole efficiency of the HVAC.

7. CONCLUSION

This document presents a method and tools to apply a Predictive Control to an air conditioning system. A simplified process has been considered for simulate and evaluate a predictive controller.

We have shown that with a predictive control it becomes possible to drive the air humidity near to the set points with minimal action. The regulator absorbs perturbations and stability is quickly reached. The behaviour of the exchanger should be modelled well enough to achieve good control performances. The expected gains are:

- achievement of the set point
- quick response to perturbations
- robustness
- power minimisation

Global design of the system is also a way of improvement. Our first approach has shown a possible benefit in connection with:

- size and mass of the exchangers
- power consumption.

Furthermore, the analysis of the refrigerating plant has shown that its performances are not included to the HVAC regulation. Thus, coupling directly the cooling plant to the air quality regulator offers opportunity to drive the operating point to an optimum point.

Two controlled variables have been assumed is this study, but in some cases control of pressure, CO_2 … is needed adding supplementary constraints. Predictive control is especially convenient to take into account these constraints and to extend to a more powerful control strategy.

In this study we have laid the basic components of an integrated design strategy to design and to control air quality (temperature, humidity, …). The next step should be to validate the concepts on a pilot plant.