

SIMTEST-ELEC: A VIRTUAL LABORATORY FOR THE TEST OF TERMINAL CONTROLLERS FOR ELECTRIC HEATING SYSTEMS FOLLOWING A DRAFT EUROPEAN STANDARD

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ABSTRACT

CEN TC247 has prepared draft standards for main types of room controllers. These standards include a performance testing procedure that was designed to facilitate the introduction on the market of electronic controllers. The test procedure is based on the connection of the real controller to be tested to a virtual (simulated) building and technical plants.

The objective of the study which is carried out in the frame of a French research project SIMTEST-Elec is the development of a testing method for control systems for electrical heating applications by emulation techniques.

The paper presents the development of models and the hardware interfaces necessary to build the test benches. Both have been carried out in Matlab/Simulink environment, an environment widely used in the control field and very suitable for emulation techniques. For each application, validation of the test bench is carried out by comparing the tests of real controllers in a real test cell with a test of the same controllers on the new virtual test bench.

The validation results show good agreement between the real test cell and the developed test bench for the test of terminal controllers. The method is now being transferred to the European CEN-TC247 committee for integration in the standard for terminal control.

INTRODUCTION

The idea of testing control systems by connecting them to a virtual building and HVAC system was first widely developed within the Annex 17 of the International Energy Agency, which involved European as well as American research laboratories. The final report of this annex was published in 1993 and proves that the approach was technically feasible. At least 6 test benches were developed at that time in Finland, Belgium, the Netherlands, United Kingdom, France and the United States of America. Numerous publications (Annex 17, 1992), (Annex17, 1993), were made and two symposiums on that topic were organised by ASHRAE in 1991 (Ashrae, 1991) and 1994 (Ashrae, 1994).

This approach has been used in the frame of the development of a European standard for terminal room controllers (CEN-TC247, 1999). The standardisation work allowed defining the methodology and procedures for the testing. In parallel to this CEN work, the European SIMTEST project (Simtest, 1998) and (Simtest, 2001) aimed in developing the necessary test equipment for these controllers: simulation models, hardware specifications, interfaces between the real controller and the virtual building. The result of these both projects was a test bench and a method to test controllers that can be used by the manufacturers or testing laboratories for product development as well as standard performance tests.

In this study in the frame of a French national research project, the existing SIMTEST laboratory has been extended to electrical applications that represent other difficulties and demands thus several adaptations of the test bench.

As a result, the new developed test laboratory is transferred to the CEN TC247 for its integration into the existing standard.

A new european association of controller manufacturers EUBAC (EUBAC, 2004) is actually developing, in collaboration with three test centers, a European certification program in order to valorise their products in the frame of the EBPD directive. Simtest and Simtest-Elec will be one of the implemented test methods.

THE TESTING METHOD OF SIMTEST

Test principle

The test principle relies on the testing of a real controller against a set of examined criteria.

A simulator including building zone and HVAC plant models within Matlab/Simulink environment emulates the environment of the real controller.

The link between real and simulated environment is achieved using a data logger and interfaces, mainly a sensor side interface and an actuator side interface (figure 1).

The sensor side interface converts the indoor temperature calculated within the zone model to a

signal that the controller temperature input can process. This is done in the considered cases by a sensor resistance simulator.

The controller determines then the control signal for the valve control. This controller output signal is used for controlling a real valve. The real drive and actuator are used because many control algorithms are adapted to specific drives. The valve position is then measured by the actuator side interface. Its output signal is fed back into the simulator via the data logger. The data logger also converts other signals of the controller such as the fan speed signals or relays.

The acquired data are then finally used in the simulator to calculate the new heating/cooling flux supplied to the building zone model resulting in a new indoor temperature.

Figure 1 shows the layout for the testing.

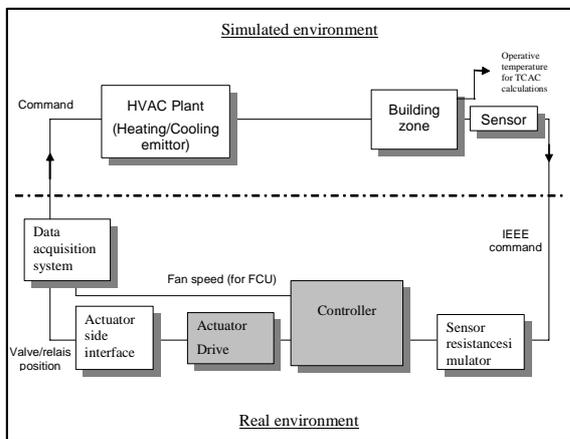


Figure 1 Test bench layout

Testing procedure and classification

Test parameters

As shown in table 1, external temperature and set point temperature are held constant during the tests. In order to introduce disturbances to the controller, the internal heat gains in the room are varied during the test. Tests are conducted by simulating three periods of 20%, 50% and 80% load conditions for HVAC emitter during heating and cooling tests as shown in figure 2.

Table 1: Test parameters

Parameter	Heating	Cooling
Temperature set point	20 °C	24 °C
Initial zone temperature	20 °C	24 °C
Outdoor temperature	-4 °C	30 °C
Internal gains	See figure 2	See figure 2
Test run duration	9 hours	9 hours

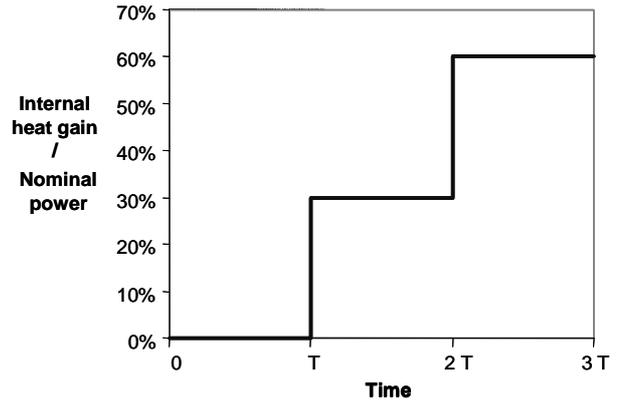


Figure 2: Time parameters

Performance classification of controller

The classification method presented here is that used in version 4 of the CEN draft standard. It is still being slightly modified, but the initial method is presented here since it has been used for the validation of the test bench.

Classification of temperature control accuracy is dependant upon Control Accuracy (CA) and Control to Set point Accuracy (CSA).

For the purposes of testing, CA and CSA are calculated for each of the three periods (a first part of 45 minutes in each period is assumed to be transient and is not considered for the calculation of the two criteria). Control accuracy (CA) is defined as:

$$CA = \text{Max}_{\text{periods 1,2,3}} |Tin_{\max} - Tin_{\min}|$$

Control to set point Accuracy is defined as the maximum difference between the mean zone temperature and set point:

$$CSA = \text{Max}_{\text{periods 1,2,3}} \left| \frac{Tin_{\max} + Tin_{\min}}{2} - \text{Setpoint} \right|$$

The Temperature Control Accuracy Classification (TCAC) of a zone is defined by a combination of CA and CSA as detailed in table below.

Table 2: Classification table

Class	CA	CSA
1	<=0.5 K	<=0.5 K
2	<=1 K	<=1 K
3	<=2 K	<=2 K
4	<=3 K	<=3 K

The worst result between the four classification parameters gives the class of the controller.

SIMTEST-ELEC PROJECT

Based on the approach described in the previous section, EDF wished to develop an equivalent test bench for electrical applications. The applications chosen are:

- electric convector
- electric floor heating
- electric ceiling heating
- fan coil unit 2 pipes / 2 wires

This paper describes the new development using the example of the electric ceiling heating and shows the steps of model development, test bench adaptation and validation.

MODEL DEVELOPMENT

Generally it has been tried to use the existing Simtest models for these new electrical applications. However, some models are newly developed for Simtest-Elec. Those were:

- emitter models: electric convector, fan coil unit 2 pipes/2 wires
- floor and ceiling heating: the existing Simtest room model does not allow the integrated calculation of electrical floor and ceiling heating. A new room model is thus developed in order to integrate these both emitter types directly in the room model.

In this paper we describe as an example the model used for the application of the electric ceiling heating. In this application, the emitter is directly integrated into the room model.

The envelope model of the room consists of a window, an external wall, an internal wall (representing three walls with adjacency to other rooms of the same temperature), a floor and a ceiling.

The heat flow between the wall surfaces by radiation is calculated using the mean radiant temperature approach with linearised heat transfer coefficients.

The thermal part of the window model is based on a steady state heat balance on the internal window surface (solar radiation is not considered in the test method, the transmitted or absorbed short wave radiation is thus not represented):

$$h_{rad} (T_{mr} - T_{surf-window}) + h_{conv} (T_{air} - T_{surf-window}) + \frac{1}{\frac{1}{U_{window}} + \frac{1}{h_{rad} + h_{conv}}} (T_{ext} - T_{surf-window}) = 0 \quad (1)$$

Each envelope element is represented by the steady state heat balance on the internal and external surfaces given by 2), as well as the transient heat balance on each internal node inside the different material layers of the wall 3) following thermal/electrical analogy:

$$h_{rad} (T_{mr} - T_{surf-wall}) + h_{conv} (T_{air} - T_{surf-wall}) + \frac{\lambda}{d} (T_{node(1)} - T_{surf-wall}) + Q_{rad} = 0 \quad (2)$$

$$m_{node(i)} c_{pi} \frac{dT_{node(i)}}{dt} = \frac{\lambda}{d_{i,i-1}} (T_{node(i-1)} - T_{node(i)}) + \frac{\lambda}{d_{i,i+1}} (T_{node(i+1)} - T_{node(i)}) + Q_{int} \quad (3)$$

Q_{int} in 3) represents the heat flow due to an electrical resistance inside one layer of the ceiling.

The calculation of the air temperature assumes perfectly mixed condition of the air. The heat balance is given by:

$$m_{air} c_{p,air} \frac{dT_{air}}{dt} = \sum_{i=1}^{n_{surf}} h_{surf(i)} (T_{surf(i)} - T_{air}) + Q_{gain} + Q_{Em} + \dot{m}_{air} c_{p,air} (T_{in} - T_{out}) \quad (4)$$

The sensor of the controller is simulated by:

$$\tau \frac{dT_{sensor}}{dt} = \alpha T_{Air} + (1 - \alpha) T_{RM} \quad (5)$$

where α is a constant representing the convective part of the sensor measurement. The time constant τ on the left hand describes the inertia of the couple "sensor element/sensor box".

The Simulink layout of the model is shown in figures 3-5. Figure 3 shows the general layout of the model with its link to the real test bench by the blocks "bench in" and "bench out". The electric ceiling heating system is directly integrated in the room model (block "Zone"). Figure 4 shows the inputs and outputs of the block "Zone" as well as its connection to the sensor model via air and radiant temperature.

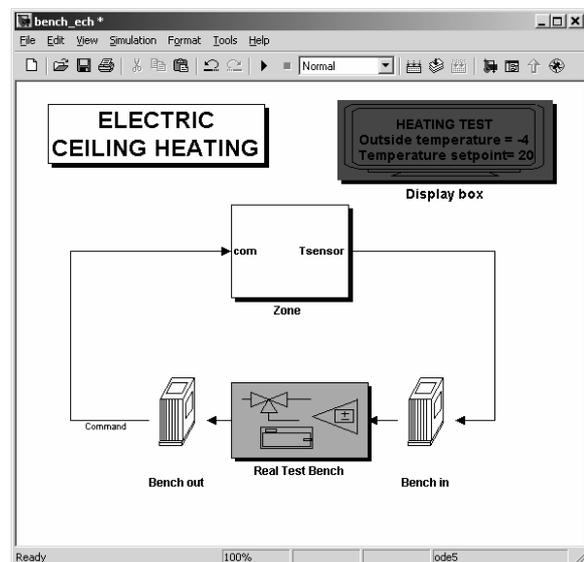


Figure 3: Test bench layout – simulation

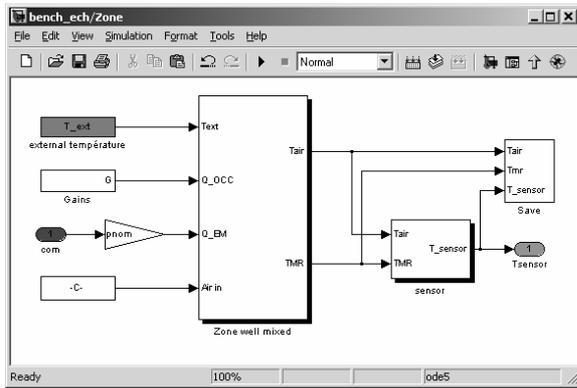


Figure 4: Zone and sensor model with in and outputs

Figure 5 gives an overview on the internal structure of the zone model with its two parts: Envelope and Zone air (based on equations 1 – 4). The loop generated by the air and the 5 surface temperatures is iterated at each time step.

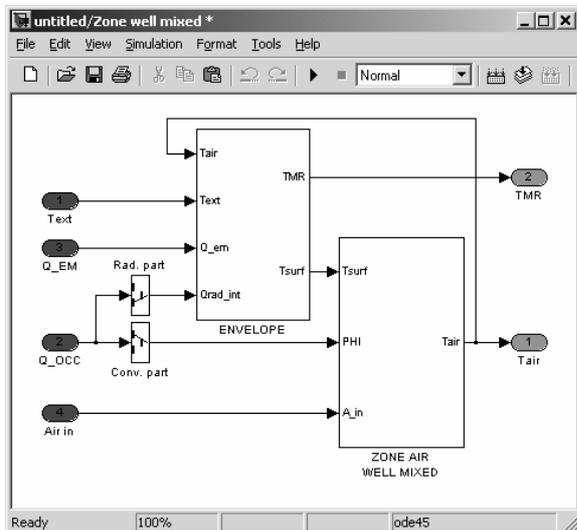


Figure 5: Room model with envelope and convection

VALIDATION OF MODELS AND THE TEST BENCH

In order to validate the test bench, measurements are carried out in a real test room (EDF – Les Renardières) equipped with the different emitters.

Experimental tests

Test cell layout

The layout of the test room is shown in figures 6 and 7. The room construction consists of brick walls and insulation (U_{wall} about $0.5W/m^2/K$). One external wall including its window is exposed to a separately controlled climate ($-4\text{ }^\circ\text{C}$ in the heating tests). The window of U_{window} about $3W/m^2/K$ has an integrated air inlet. Air is extracted at the opposite side of the test room by mechanical extraction with flow measurement. One other wall (wall N°4) of the room can be conditioned by a water flowed panel that

allows to increase the heat losses (cooled wall in figure 6). Figure 7 also shows the integrated ceiling heating that is composed of 13mm of plaster covering, electric resistance film layer and 200 mm of mineral wool (from internal to external).

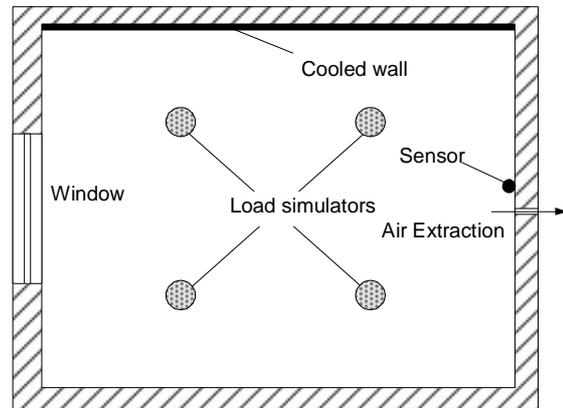


Figure 6: Test bench layout – plan view

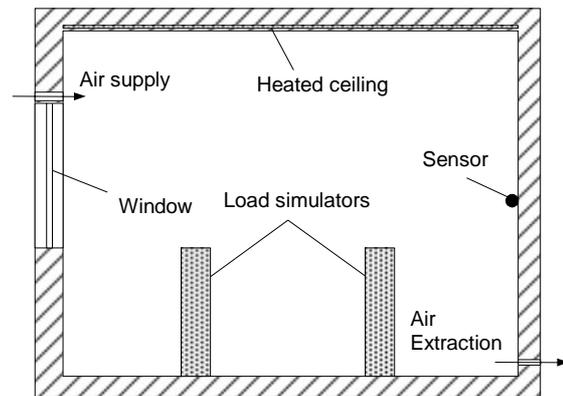


Figure 7: Test bench layout – section view

Load simulators are placed symmetrical in the room. The radiant and the convective parts as well as the inertia of the simulators have been estimated by measurement.

External and conditions at each side of the room can be controlled. Except the external climate and the cooled wall these temperatures were inbetween 20 and 22°C and were also measured. Data acquisition is carried out for around 40 measurement points at a time step of 30 seconds. These measurements include also surface temperatures, temperature profile inside the room (air and globe temperature) etc.

Procedures for validation tests

Two types of tests, open and closed loop tests are performed. The open loop test with 4 different periods are essentially used to fit and validate the simulation models. This fit consists in choosing the most appropriated convective heat transfer coefficient for floor, ceiling and walls inside the range of realistic values (eg. $2 - 4\text{ }W/m^2/K$ for vertical walls).

The closed loop test is carried out using a real controller for the electric ceiling, available on the market. The results of this closed loop test are then firstly used to check again the simulation models (the inputs as eg. the heat load of the heated ceiling are essentially taken from measurement) and finally to compare this real test to a test of the same controller on the new test bench (the setpoint and parameters of the controller being blocked).

The scenarii of the two tests are given in tables 3 – 4. During the tests, the external temperatures are kept constant.

In the open loop test (table 3), heat gain and load of the emitter are varied in order to obtain different load situations that allow the validation in different regimes.

Table 3: Open loop test schedule

	Per. 1	Per. 2	Per. 3	Per. 4
Twall 4 [°C]	14	14	14	14
Text [°C]	-4	-4	-4	-4
Tadj [°C]	22	22	22	22
Heat gain [W]	0	0	400	400
Load [%]	0	100	100	0
ACH	0,5	0,5	0,5	0,5

The closed loop test (table 4) is designed identical to the standard tests in the Simtest project. Three periods with 0, 30 and 60 % internal heat gains (normalised to the nominal load of the emitter) lead to a varying load of the emitter of 80, 50 and 20% of the nominal if the temperature is controlled to the set point temperature.

Table 4: Closed loop test schedule

	Per. 1	Per. 2	Per. 3
Tsetpoint [°C]	20,5	20,5	20,5
Twall 4 [°C]	14	14	14
Text [°C]	-4	-4	-4
Tadj [°C]	22	22	22
Heat gain [W]	0	30	60
Load [%]	80	50	20
ACH	0.5	0.5	0.5

Validation of simulation models

For all validations, a resultant temperature is defined as the average of air and the area-weighted surface

temperatures. Both values are available from measurement and simulation results.

Open loop validation

As shown in figure 8, the resultant temperature fits well with the measurement for periods 2-4. In period 1, when the test room is not heated at all, the difference is about 1.5K. This is probably due to the changing heat transfer coefficient which is different in this period. However, this case is not possible on the standard test bench, the difference can thus be neglected.

In the transient period, simulation follows in good agreement the measurements.

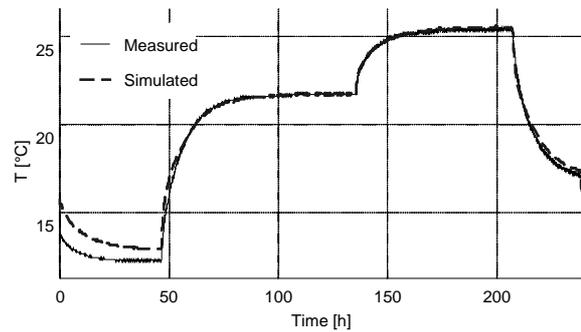


Figure 8: Test bench layout

Closed loop validation

This simulation is carried out with the same heat transfer coefficient obtained from the open loop test. The maximum difference is about 1 K in the beginning of the test, mainly due to the initialisation of the simulation at the beginning of the test.

Simulation responds slightly faster than the measurements indicate.

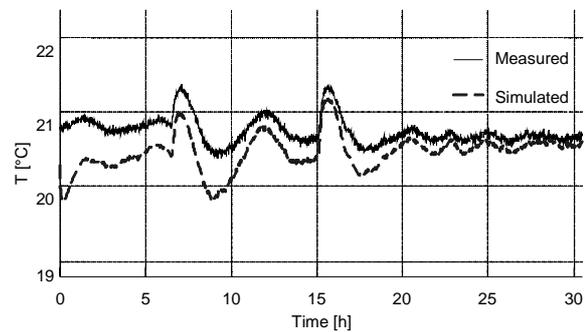


Figure 9: Test bench layout

Validation of test bench

In this test, the results of the closed loop test are considered. The controller is now installed on the Simtest-Elec test bench including the interfaces shown in figure 3. These are the resistance of the

temperature sensor (characteristics have been obtained from the manufacturer) on the “bench in” side and the command of the relays of the controller on the “bench out” side.

The parameters as well as the set point temperature of the controller have been blocked before the real test in order to run this test with exactly the same configuration.

Qualitative comparison of temperature evolution

The qualitative comparison of the test results shows good agreement between the closed loop test in the test room and the closed loop test on the test bench (figure 10).

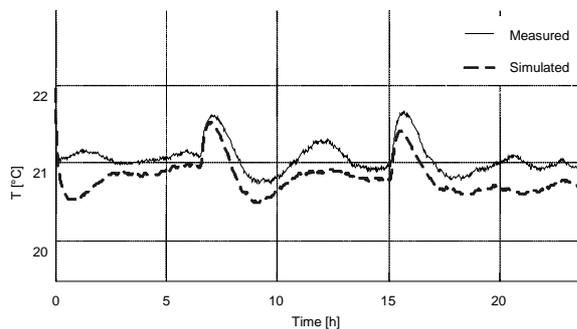


Figure 10: Test bench layout

In the initialisation phase of the test, a difference is observed. This is not relevant since the standard previews an initialisation phase. For the rest of the test, the results agree very well. The mean values of the temperature is slightly lower on the test bench, this could be due to the position of the controller box near the wall or convective phenomena around the sensor box or even the choice of sensor parameters in the model.

Validation by classification results

The aim of the validation is to obtain an identical performance class of the controller in the real test room and on the virtual test bench using the classification scheme of CEN TC247.

As indicated in table 5 the performance criteria CA and CSA fit very well with the results obtained in the real test room. The criteria CA is nearly identical, indicating the transient effects are accurate on the test bench. In the case of CSA, the offset that has already been observed in the qualitative comparison by temperature inspection is confirmed by a higher value on the test bench, but the class of CSA is still the same in real and virtual test.

The final class of the controller is 2 in both cases, the virtual test bench can thus be considered as acceptable.

Table 5: Validation of classification results

Controller classification				
Index	measurement		emulation	
	Value	Class	Value	Class
CA	0.73	2	0.75	2
CSA	0.47	1	0.20	1
Class	2		2	

Results of the other electrical applications and perspectives

The validation of Simtest-Elec in the other three applications was successful.

In the case of one controller for the application of the heated floor, the virtual test bench was not able to reproduce exactly the results of the real test. This was due to a specific problem of controllers for electrical applications: in many controllers, the electric current passes inside the controller box which contains at the same time the temperature sensor. The electric current (or resistance) causes a supplementary heat gain inside the sensor box that disturbs the measurement of the temperature sensor. In order to deal with this problem, controller manufacturer “correct” the measured result by a specific law in their control algorithm, mostly obtained by measurement in a test room. This correction can attend easily 5 K which makes a test on the virtual test bench impossible.

In a second project, EDF and CSTB develop an additional feature for the Simtest-Elec test bench allowing to test also those products. On this new test bench, the controller is installed into a climatic box where the same conditions (temperature and air velocity) are reproduced as in a real room. This allows also to remove the resistance simulator of the actual test bench.

CONCLUSION

It has been shown that simulation models for testing control systems for HVAC applications have been successfully developed and implemented in the MATLAB/SIMULINK environment. The models have been especially developed with towards testing applications, meaning that the important modelled features are selected such that they are sufficient for these applications. The models have been validated in open loop and closed loop tests. For the closed loop cases, the test bench including all the interfaces between the simulated environment and the real controller was also validated by comparing

measurements with real test cells with the emulated tests. The graph inspection and the classification comparison showed a very good correspondence between the measured and emulated controller testing methods.

The emulation method was successfully validated such that it is accurate for its application in standard tests.

The method is already transferred to CEN TC247 for its implementation in the standards.

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