Space heating control of an individual dwelling by a fuzzy controller acting on the flow rate of a heating floor

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SUMMARY

A lot of complementary solutions to save energy in buildings already exist. If it is well insulated, a building can produce itself a part of its thermal energy consumption, tanks to renewable energy devices such as solar collector. This clean energy mustn't be spoiled; therefore a good control must be applied to its use. The fuzzy control is one of these solutions. We applied it to the control of the heating floor of an individual dwelling. The design and the validation of the controller were carried out in simulation with the software TRNSYS 16.

INTRODUCTION

The integration of renewable energies in a dwelling is a complex process. Many devices are able to produce clean and cheap energy. It concerns electrical energy, domestic hot water and heating. However, this clean energy must be optimized by the consequent control of the actuators using this energy.

Heating floors are one of the most interesting heating devices. They produce a high comfort level to the user and are supplied by a low temperature heating fluid, which facilitate the integration of renewable energies. Energy savings could be made if we could lower their operation level when it is possible during the inoccupation periods in the dwelling. This would optimize the performances of the heating floor and in the same time lower the use of boilers using fossil combustible or electrical energy from the grid.

Since 2005 a partnership between AMPERE and CETHIL and supported by the Region Rhone Alpes carried out a study on the design of a global controller which could optimize the contribution of renewable energies and control the thermal and electrical comfort. Concerning the thermal comfort, the testing of our temperature control procedures requires a reference control to be compared to and appropriate testing conditions. For this reason, we use simulation to test our controller in different buildings. One of these building is the model of a dwelling designed in the process of the Task 26 lead by the International Energy Agency [1]. This model was designed to test the performances of existing solar combisystems, and was chosen for its quality and its simplicity. Our reference controller is a fuzzy controller, one of the most accurate controllers sold to the public. Fuzzy controllers are usually used for office buildings which are occupied during the day and unoccupied during nights and week end. For our dwelling, occupation and inoccupation periods are inverted, which is more unusual. This study will show the interest of this adaptation.

We tested its performances in this house, which we located in Lyon, France.

DESCRIPTION OF THE MODEL

Description of the building

The building we chose is a single family home. Its surface is 140 m² large and it is located on two levels. It was designed to consume 60 kW.hr/m²/year for space heating in Zurich, Switzerland, which represents good thermal performance [1]. It is modelled in TRNSYS 16 with type 56 and the interface TRNBUILD.

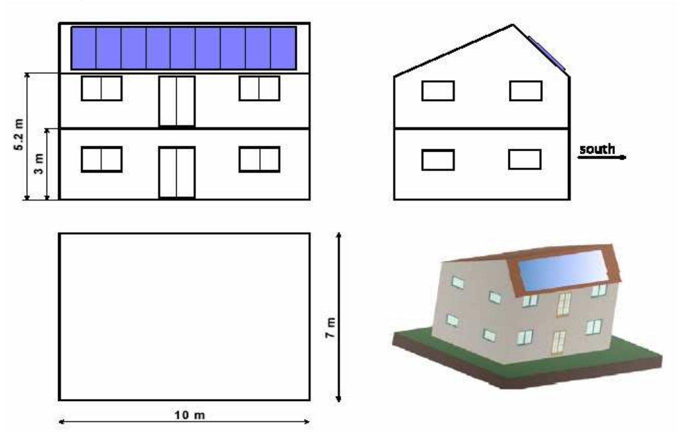

Figure 1: The task 26 dwelling

Windows are double glazing, modelled with type 2001 from the TRNBUILD library.

Table 1: Windows surface

Wall's orientation	North	South	East	West
Windows surface (m²)	3	12	4	4

Table 2: Walls description

Wall	Orientation	Surface [m²]	Conductance [W/m²K]
External Wall	North	50	0.342
External Wall	South	50	0.342
External Wall	West	40.5	0.342
External Wall	East	40.5	0.342
Roof	North	61.4	0.227
Roof	South	25	0.227
Ground	Horizontal	70	0.196
Internal Wall		200	2.686

Description of the thermal energy production systems

For the heating space, we integrated a solar collector and a wood boiler. The surface of the collector is 20 m². Its efficiency is modelled by second order quadratic function.
The boiler was in the first design of the IEA a gas boiler but it will be a wood boiler in our case. Its power is 15 kW, its efficiency is 90%.
The solar collector and the boiler are connected to two loops which supply with hot heating fluid two heat exchangers in a storage tank. This tank is a cylinder tank, it is 1,7 m high with a volume of 0,5 m^3. The tank is heated in priority by the solar collector. Its pump is activated as

soon as the temperature of the fluid exiting the collector is 5°C higher than the tank's bottom's temperature. If the temperature of the tank diminishes lower than 50 °C, the pump of the wood boiler is activated until the temperature of the tank reaches 70°C. The tank also heats domestic heat water.

Table 3: TRNSYS types used for the simulation [2].

System	Type	Details
Solar Collector	Type 1	TRNSYS library
Boiler	Type 700	TESS library
Storage Tank	Type 60	TRNSYS library

Description of the heating floor

The house is heated with a heating floor similar to the floor modelled in the Task 26 [3]. Its surface is 140 m² large, the two stages are supplied with two different loops. It is modelled directly in the definition of the floors of the building. The pipe grid is defined as an active layer of the floor. The pipe spacing from centre to centre is 10 cm, the outside diameter of the pipes is 2 cm. The heating fluid has a 30% glycol fraction, is mass heat is 3.74 kJ/kg. A diverting valve maintains the incoming fluid temperature around 35 °C. The heating fluid is heated in a heat exchanger in the storage tank.

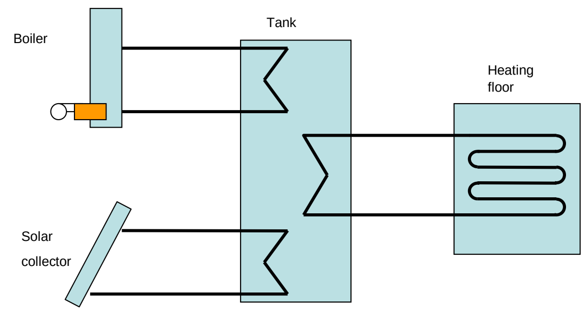

Figure 2: Hydraulics scheme of the dwelling

THE FUZZY CONTROLLER

Principle of fuzzy control

Among the temperature controller available nowadays, we can found the fuzzy controller. Based on fuzzy logic [4], it controls the temperature when the building is occupied and also estimates the necessary time to restart space heating before the end of the inoccupation periods to make sure that the temperature respects the high set point when the next occupation period begins.

Fuzzy logic is a command law which is calculated according the variation of some chosen variable. Considering the case of a single variable e, a grid is realized on the interval $[e_{\min}, e_{\max}]$ defined by the user, which is supposed to be representative of the possible variation of e. We get an ensemble of nodes $\{e_{\min},...,e_i,...,e_{\max}\}$ and sub intervals. To each node e_i corresponds a command value $\mu(e)$, set by the user. For an unspecified e, the command $\mu(e)$ is calculated as following :

$$\text{if } e < e_{\min},\ \mu(e) = \mu(e_{\min})$$
$$\text{if } e > e_{\max},\ \mu(e) = \mu(e_{\max})$$

if $e \in [e_i, e_{i+1}]$, then

$$\mu(e) = \mu(e_i)\frac{\mu(e_{i+1}) - \mu(e)}{\mu(e_{i+1}) - \mu(e_i)} + \mu(e_{i+1})\frac{\mu(e) - \mu(e_i)}{\mu(e_{i+1}) - \mu(e_i)}, \qquad (1)$$

In the case of n variables, a *n*-dimension grid is realized and a value $\mu(N_i)$ is set for each node N_i. The command value of an unspecified vector V is the average of each $\mu(N_i)$, taking only the nodes which define the net to which *V* belongs. This average is balanced by the distance of each node N_i to V.

Use of the fuzzy controller in the building

The controller controls the temperature of the building in varying the flow rate of the heating fluid in the heating floor.
The user must first define the periods of occupation and inoccupation in the building. Then he sets the high temperature level for occupation and the low temperature level for inoccupation. The management of inoccupation consists in to steps. The first step consists in turning off the pump of the heating floor, which leads to the descent of the temperature until it reaches the low temperature level. The controller maintains then the temperature of the building around this level. The second step is the restart step. The controller calculates the time when it must produce the maximal flow rate in the heating floor, in order that the temperature reaches the high temperature level at the moment when the occupation period begins. On each time step, the controller calculates the time needed for the temperature to reach the high temperature level. If it is longer than the time before the next occupation period, then the restart step begins and the command is set to its maximum. The restart time is calculated in function of the external temperature and the internal temperature of the building.
The variations intervals are respectively determined between the minimal external temperature which depends of the climate and the high temperature level and between the low and high temperature levels. The restart duration *t* is a linear function of the external temperature T_e, that's why only two nodes are used for the grid on this variable. We use seven no des for the variation of the internal temperature T_i, to guarantee the best precision. The fuzzy function which defines the restart time for each node $(T_{e,j}, T_{i,k})$ with $(j,k) \in \{[1;2],[1;7]\}$is:

$$t_{(T_{e,j},T_{i,k})} = \alpha \frac{T_{\max} - T_{e,j}}{T_{\max} - T_{\min}} \left(\frac{T_{i,k} - T_{\max}}{T_{\max} - T_{\min}} \right)^3, \qquad (2)$$

We have $T_{\max} = 20$ °C, $T_{\min} = -10$ °C, and $\alpha = 10000$ hr. The two first values are defined by the weather conditions. The last one has been empirically chosen.
For the occupation periods, we also use fuzzy control to calculate in function of the internal and external temperature the best flow rate command for the heating floor which will maintain the temperature of the building around the high temperature level. Seven nodes are used on both variables. The fuzzy function which defines the flow rate for each node $(T_{e,j}, T_{i,k})$ with $(j,k) \in \{[1;7],[1;7]\}$ is :

$$Q_{(T_{e,j},T_{i,k})} = Q_{\max} + \frac{Q_{\min} - Q_{\max}}{6}(j-1) - \beta \frac{(6-k)}{6} Q_{\max}, \qquad (3)$$

For the simulation, we have $Q_{\max} = 700$ kg/hr, $Q_{\min} = 0$ kg/hr and $\beta = 0{,}3$.

STUDY OF THE CONTROLLER'S PERFORMANCES

Description of the simulation

The controller was set with inoccupation periods between 6 A.M. and 7 P.M., from Monday to Friday. The low temperature level is set on 10°C and the high temperature level to 20°C. The real inoccupation periods are between 8 A.M. and 7 P.M., but the inertia of the building is such that the descent step can be anticipated. The flow rate of the heating floor can be set between 0 and 700 kg/hr, the fluid's temperature is set to 35 °C. However, our modelling choice imposes minimal flow rate value in the floor : the floor is divided in a limited number of nets. The lower is the minimal limit, the greater is the number of nets. 250 kg/hr is the lower limit our simulation program can bear.
Furthermore, 200 litres of domestic hot water, temperature 45°C, is produced each day. The simulation takes place in Lyon Bron, France, during the two first week of January. The time step is 6 minutes. We monitored three phenomena: the first one is the evolution of the temperature in the building. To satisfy our performance criterion, the temperature must remain around the high temperature level with a limit of more or less 0,5°C during the occupation periods. The second one is the evolution of the heating power supplied by the heating floor to the building. We will estimate the energy spent to heat the dwelling. The last one is the evolution of the tank temperature and the evaluation of the energy supplied by the solar collector and the boiler.

Results

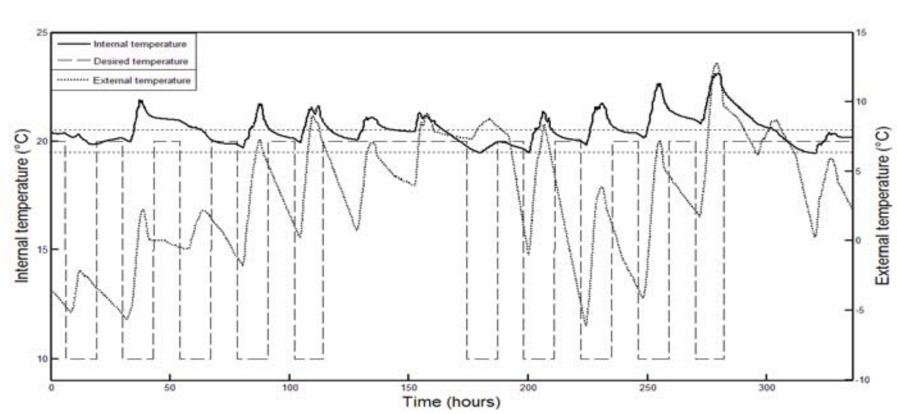

Figure 3: Evolution of the temperature in the dwelling

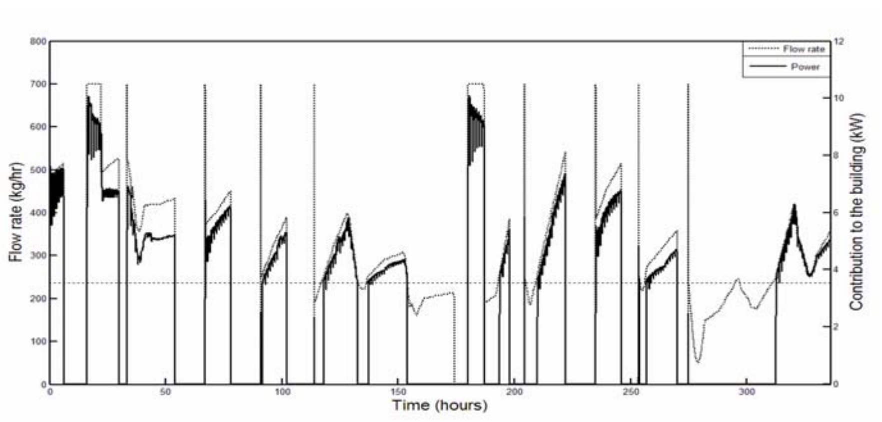

Figure 4: Flow rate and power of the heating floor

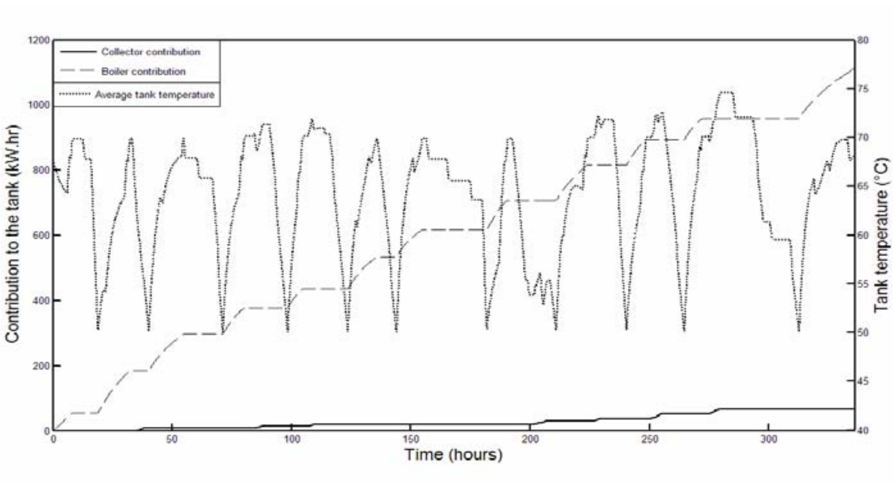

Figure 5: evolution of the temperature of the tank

Analysis

We notice on figure 3 that our criterion is verified during the week, excepted during the first Tuesday and the second Thursday when some overheat can be noticed. The control during the week end is more delicate, the temperature is sometimes too high. We also observe that the temperature doesn't necessarily decrease during the occupation period. The solar gains are sometimes so high that the temperature increases even if the heating floor is turned off. This is the same phenomenon which produces overheats during the week end, since these solar contributions aren't taken into account by the controller during the occupation period. If the temperature somehow decreases during the inoccupation period like during the first and the second Monday, the restart time is well evaluated and the following occupation period begins with a 20°C temperature.

We notice on figure 4 that the heating power given to the building is proportional to the flow rate in the heating floor. This power is null during the inoccupation period, excepted during the restart stage. If the temperature doesn't decrease during the inoccupation period lower than the high temperature level, the restart stage is skipped. The controller actually considers this stage during one time step, that's why we can notice thin flow rate peaks on the beginning of some occupation periods.

The biggest problem of the controller is the fact that it keeps heating the building whereas the temperature is already too high. This is the consequence of the minimal flow rate limit, we have to make sure that the calculated flow rates remains above the limit most of the time, which sometimes leads to overheats.

The total energy contribution of the heating floor to the building is 890 kW.hr

We notice on figure 5 that during these two weeks, the solar gain to the storage tank is low. This could be expected since in this season the solar radiations are weak. We will however notice that the final solar gain is 64 kW.hr and the boiler gain is 1115 kW.hr.

COMPARISON WITH A LINEAR CONTROL METHOD

Control method

Our fuzzy controller passed the test of our criterion, despite some high temperature sometimes and some limitations from our model. We will now compare its performances to a standard linear control.

The flow rate is calculated in function of the external temperature the following way :

$$Q_c(T_e) = Q_{max} \frac{T_{max} - T_e}{T_{max} - T_{min}}, \qquad (4)$$

Q_{max}, T_{max} and T_{min} are empirically determined in order to get the best performances. T_{max} and T_{min} delimit the usual variation interval of the outside temperature.
In our case, we respectively chose for those three values =450 kg/hr, 20°C and -15°C.
The goal is to constantly maintain the temperature around the same temperature level of 20°C.

Results

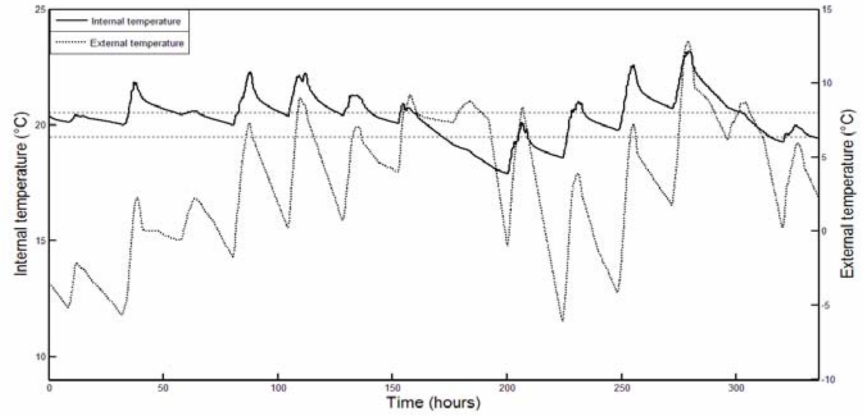

Figure 6: Evolution of the temperature with a linear control

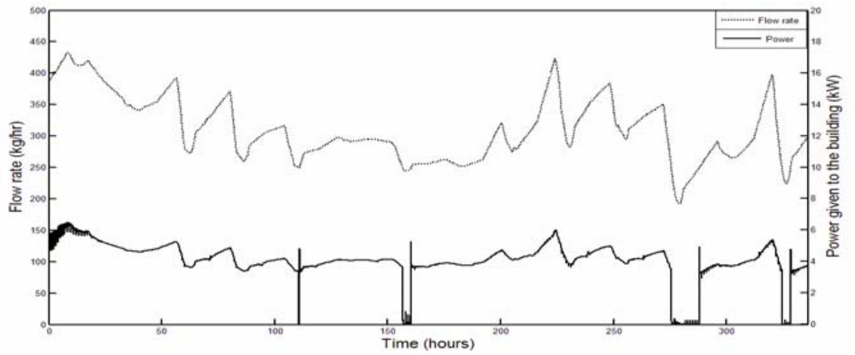

Figure 7: Flow rate and power of the heating floor with a linear control

Analysis

The performance criterion in this case for the temperature control is still to keep the temperature in the $20 \pm 0{,}5°C$ area. But this time, this criterion prevails during the whole simulation, when it only mattered during the occupation period for the fuzzy controller. We can't therefore make a quantitative comparison to determine which controller best respects the criterion but we can somehow make qualitative comparison.
We can see on figure 6 temperature risings on the same moment like on figure 3. The cause of these peaks is the same: the solar contribution isn't taken into account by the controller. However, the amplitude of these peaks is greater with the linear controller. Since the solar contribution happens during the inoccupation period, the fuzzy controller turns the heating

floor off and compensates the solar gain. The linear controller makes no difference and keeps heating while the internal temperature is already too high.
We also notice that the temperature decreases twice below 19,5°C. We can conclude that the fuzzy controller produces a better control than the linear controller.
The calculated flow rate remains between 200 and 450 kg/hr. We can confirm the proportional relationship between the flow rate and the heating power.
The heating power contribution to the building is 861 kW.hr, 3,7% less than the fuzzy controller. The boiler contribution to the tank is 914 kW.hr and the collector contribution is 69 kW.hr.

CONCLUSION

In our study, the fuzzy controller doesn't save more energy than the linear controller.
However, its control is better than the linear controller since it takes profits of the solar gains and the inertia to lower the restart step duration.
The fuzzy controller is a powerful controller but it is limited by its simple rules. It handles well the inoccupation periods, but this capacity doesn't save much energy, because of their short duration. It will in spite of that be our reference to compare the performances of a new controller which we started to design.
Our strategy consists in using advanced automation techniques such as optimal command [5] to improve the exploitation of inoccupation periods and predictive command to better anticipate external gains such as solar gains and internal gains, caused by inhabitants and electric devices. We will also use a state system modelling to anticipate on its behaviour.

ACKNOWLEDGEMENT

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