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Room air conditioner load control under summer comfort constraint

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ABSTRACT

Load control options interest is growing because it can represent a response to future network investments and to congestion problems. In this frame, the present paper gives a methodology to quantify the value of load control for heat pumps (room air conditioners), in small tertiary and residential buildings, considering the occupant's comfort and the electrical grid needs for load shift.

This methodology was applied to a small office building where simulations were made using TRNSYS software.

It was found that a significant demand relief can be achieved by load control. However each control is followed by a recovery effect, which causes high peak consumption. In terms of comfort, this study shows that during the summer season some control strategies can be applied without affecting the occupant's comfort. Nevertheless during a heat wave comfort conditions are not achieved.

1. INTRODUCTION

Increasing interest in demand side management strategies appear more and more as a solution to electrical network problems. These problems include the need for future network investments, an increasing peak power consumption, transmission and distribution congestion problems which can be solved or reduced with the implementation of DSM strategies and smartgrid equipments.

Strategies such as load control can have a large impact in the resolution of these problems, especially in system stress situations. However there is a lack of methodologies to quantify the benefits and costs of DSM (Strbac, 2008).

DSM strategies can be applied to several electrical appliances, like HVAC systems, hot water heaters, washing machines and others.

In France, there is an important summer electrical gradient of 500 MW/°C (RTE, 2009). Regarding the load shift potential, and due to its coincidence with the summer electrical peak (Figure 1), around 13h (1p.m), heat pumps control load can have big impact in stressed electric networks.

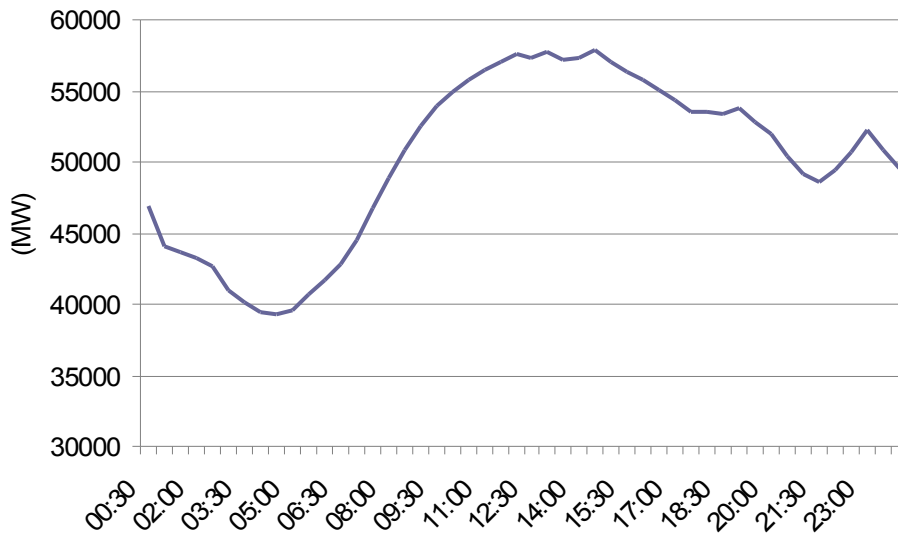


Figure 1 – French typical summer load curve (Réseau de transport d'électricité)

Regarding flexibility, systems that can store electric energy in another type of energy (for example thermal energy) are among the most interesting for DSM (Stadler, 2008) because they allow longer curtailment times and can be combined with heat pumps. In this article we focused on heat pumps (“reversible split systems”), without any type of heat pump storage component (like cold water tanks), considering only the building thermal inertia as a flexibility component.

Reddy (Reddy, T.A et al., 1991) developed a methodology to evaluate load curtailment potential of an air conditioner as a function of building thermal inertia. Nevertheless his analysis was based in a simple equivalent thermal parameter (ETP) model (one resistance and one capacity) that does not reflect the real temperature fluctuation in a building (ORPHELIN, 1999)

Srinivas (Srinivas & Ning, 2006) evaluated different control strategies applied to HVAC systems. However the impact of different external conditions, during a control, regarding peak power and the subsequent comfort impact are not quantified.

Advanced control strategies were studied by Kyoung-ho (Kyoung-ho & Braun, 2008), where the heat pump control takes into account the building thermal mass and occupants to create an optimized pre-cooling. Although this strategy seems to be very attractive, advanced control is needed to correctly apply this strategy. Since this article is focused on small tertiary and residential buildings this kind of strategies will not be evaluated.

In this paper a methodology is developed to quantify the value of different load control strategies for room air conditioners (RAC), in small tertiary and residential buildings, taking into account occupant’s comfort, defined in EN 15251 (EN 15251, 2007), and the electrical grid needs for load shift.

2. SIMULATION METHODS AND EQUIPMENT SPECIFICATION

2.1 Simulation characteristics

To be able to couple Multizone building thermal evolutions with the RAC operation, a set of simulations was done with TRNSYS software (TRNSYS, 2000), where the energy effects (positives and negative) and comfort impacts of heat pump control load shift could be determined. These simulations make possible a random characterization of the control impacts due to weather evolutions. A small office building with two floors and a total surface area of 1000 m², representing 25% of the French stock, was chosen (Andre, P. et Al., 2009). The building plan is the same for the two floors and it is shown hereafter.

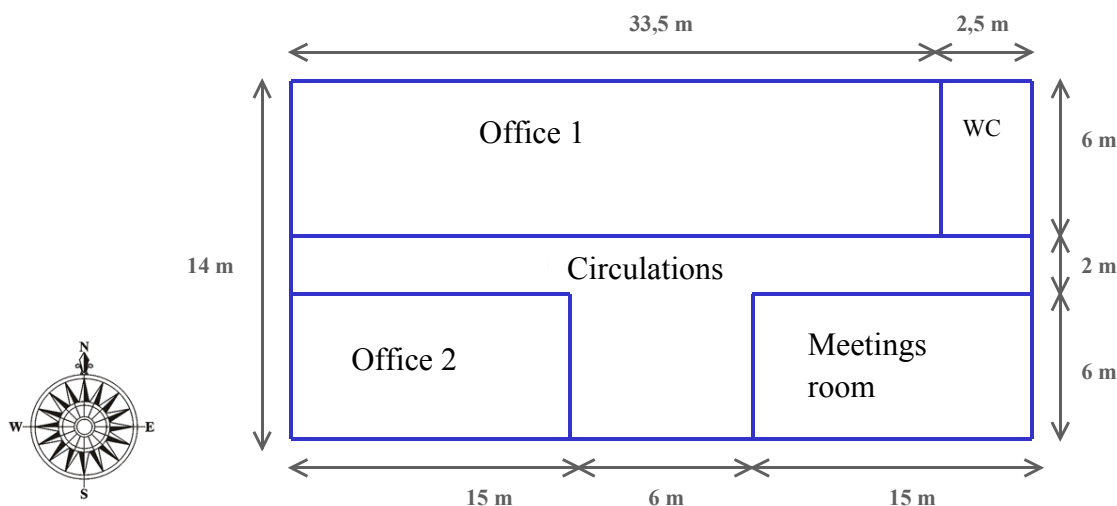


Figure 2 – Building plan

The building is simulated for the “Nice - France” climate using *Meteonorm data*, since this region suffers congestion and peak consumption problems during summer.

In order to simulate the heat pump (room air conditioner) operation, full-load and part-load, a model created by Marchio and Filfil (Marchio & Filfil, 2004) was implemented in *TRNSYS* and coupled to the building. Standard manufacturer parameters were used in this study.

For each building room the heat pump power was dimensioned for the maximum sensible and latent needs. Since almost all split heat pumps available in the market do not control humidity in the room, we considered a surplus of 20% of capacity to take into account the latent loads.

Simulations were made with a 1 minute time step to be able to correctly evaluate the comfort impact of each load control strategy.

2.2 Heat pump control and comfort criterion

To correctly consider the occupants comfort, the recommended interior operative temperatures for energy calculation, category II, from the EN 15251 were considered (EN 15251, 2007).

Table 1 – EN 15251 - Temperature ranges for energy calculations

| <i>Type of building / space Category</i> | <i>Acceptable T_{op} (°C) range</i> | |
|--|--|------------------------------|
| Offices and spaces with similar activity Sedentary activity ~1,2met* | Heating season ~ 1,0 clo** | Cooling season ~0,5 clo** |
| | I 21,0 – 23,0 | I 23,5 – 25,5 |
| | II 20,0 – 24,0 | II 23,0 – 26,0 |
| | III 19,0 – 25,0 | III 22,0 – 27,0 |

*met – metabolism rate

**clo - unit that defines the equivalent insulation provided by clothes

There is a difference between the heat pump control temperature (air temperature) and the operative temperature, which is used to define comfort conditions within EN 15251 (EN 15251, 2007). Caillet (Caillet, J. et Al., 2009) has shown that a constant air temperature set point is not able to guaranty comfortable operative temperatures, taking into consideration the EN 15251 temperature ranges.

To simulate occupants' behavior, it was supposed that the occupants can interact with each RAC air set point at the end of each hour to achieve an operative temperature of 24.5 °C, during occupation hours, achieving this way a comfortable operative temperature. As it can be seen in Figure 3, to achieve an operative temperature around 24.5 °C, at 1 p.m, the heat pump set point needs to be set to 22.3 °C, e.g. to maintain a constant operative temperature the set point must vary with the building cooling loads.

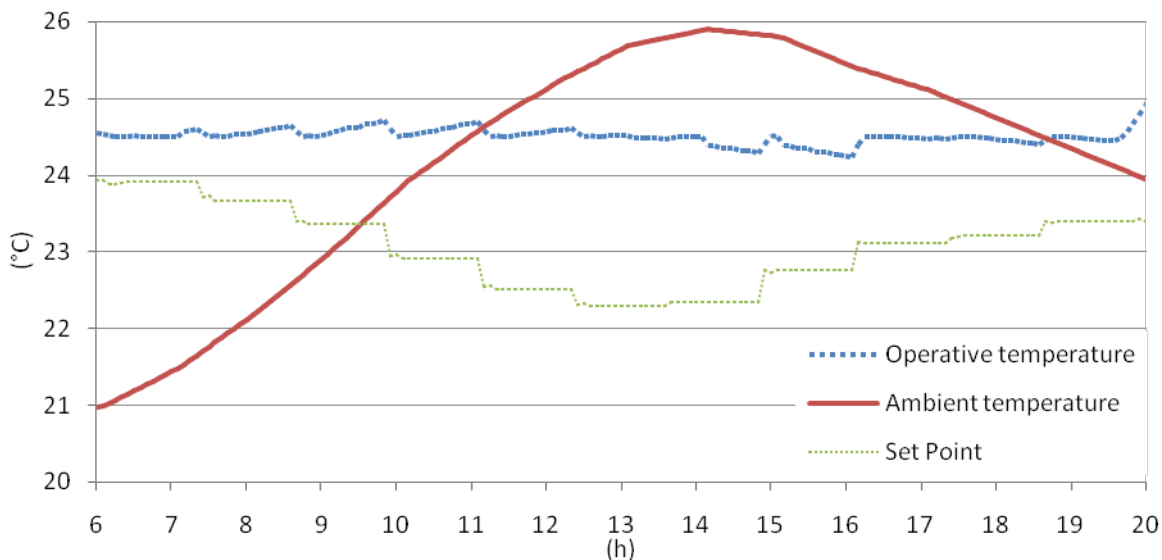


Figure 3 – Effect of occupant's compartment over the set point temperature

However during a control strategy, it is assumed that the occupants can stand an operative temperature of 27°C, passing from the equivalent 10 % PPD to 15 % PPD¹, or assuming that a ventilator is available in the room, increasing the temperature tolerance at the maximum of one degree (according to EN 15251).

The thermal comfort is evaluated in the room with the larger cooling needs (“Office 2” south orientation – Figure 2). This way the maximum discomfort is quantified and it is ensured that other rooms will have a lower comfort impact.

2.3 Control strategies for load curtailment

For each strategy applied there can be more or fewer gains in terms of power consumption reduction, however their comfort impacts can be very different. To evaluate the potential of load shift and load reduction strategies during the French summer electrical network peak, three load control strategies were selected:

¹ - PPD – Percentage of Person Dissatisfied

- i. Total Load curtailment (TLC) – one hour operation suspension
- ii. Multiple load curtailments (MLC) – two times 30 minutes operation interdiction with a time interval of 30 minutes between them (combined interdiction: 30 + 30 = 1 hour)
- iii. Capacity reduction (CR) – Reduction of the heat pump capacity by 50 % for two hours

Each one of the selected strategies is evaluated, in terms of energy impacts, for the entire building.

Our study is focused in the French electric network, where the electrical network peak occurs normally around 1 p.m every summer day working. So the described strategies were applied each day of the cooling season at 1 p.m and compared with the reference case (normal operation without control strategy). This way the energy and comfort value of each strategy can be evaluated for the entire cooling season.

During heat waves the electric network becomes less reliable due to congestion problems and peak consumption (electric thermal gradient). Therefore emergency load controls can play an important role, avoiding severe problems like black-outs. To evaluate the role of the selected strategies during a heat wave, simulations were made for during ten consecutive days, where the daily average temperature was 24°C.

2.4 Analysis indicators definition

The heat pump operation is a function of the building thermal state. It is expected that, if a load curtailment control is applied to a heat pump, the building thermal will change. Imagining load curtailment on a hot day, the building temperature will raise, meaning that when the heat pump is turned on again, it will have to compensate the energy that was absorbed by the building (Figure 4 - overconsumption).

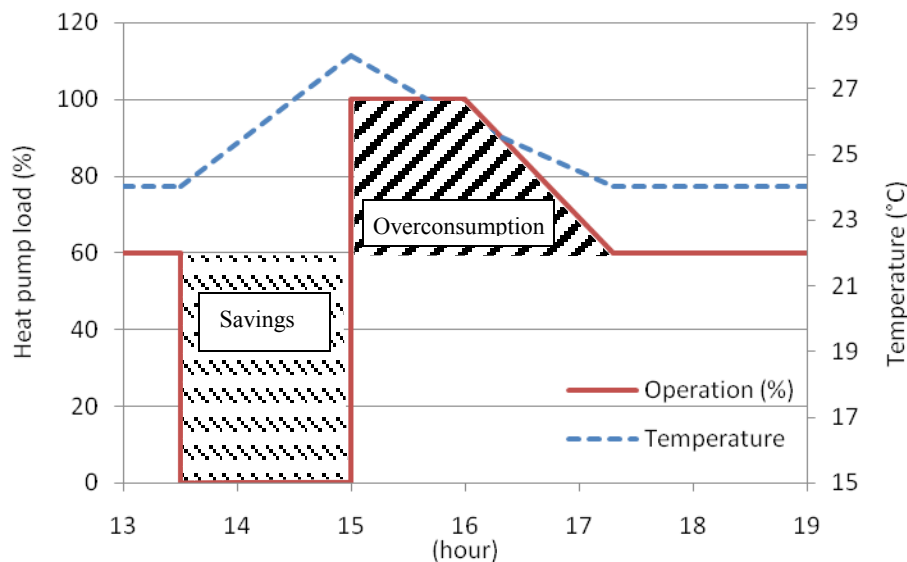


Figure 4 – Effects of heat pump load control

In order to analyze the energy effects and the discomfort caused by a heat pump load control, we define, hereafter, the following indicators:

- *Total consumption [Wh / m²]*: Total heat pump consumption during the whole day per square meter (total building surface)

- *Energy savings during control [Wh / m²]*: energy consumption per square meter (total building surface) difference between the reference case (normal operation) and the case with load control, for the period where the control is applied.
- *Overconsumption [Wh / m²]*: energy consumption per square meter (total building surface) difference between the reference case (normal operation) and the case with load control, for the period after the control.
- *Recovery (%)*: $\frac{\text{Overconsumption}}{\text{Energy savings}} \times 100$: indicates the quantity of energy that is consumed after the control compared to the energy saved during the control.
- Degree-hours of discomfort:

$$DH = \int \text{Max}[(T_{\text{indoor}} - 27^{\circ}\text{C}), 0]dt \quad (1)$$

, where T_{indoor} and t is time

- *Non comfortable days*: percentage of the days, during the whole cooling season where there room is considered as uncomfortable (when the operative temperature is higher than 27°C)

3. RESULTS

Hereunder we present the average results for the whole cooling season.

3.1 Energy and power saved by load curtailment

In table 2 we present the average results for each control strategy regarding their energy effects.

Table 2 – Energy effects for the different control strategies

| | <i>Total consumption [Wh / m²]</i> | <i>Energy savings during control [Wh / m²]</i> | <i>Overconsumption after the control [Wh / m²]</i> | <i>Recovery [%]</i> |
|--|---|---|---|---------------------|
| <i>Total curtailment (TLC)</i> | 80.36± 24.26** | 16.04 ± 5.58** | 11.26 ± 3.10** | 75 ± 17** |
| <i>Multiple load curtailment (MLC)</i> | 80.36± 24.34** | 15.67 ± 5.64** | 10.89± 3.13** | 75 ± 19** |
| <i>Capacity reduction (CR)</i> | 81.50± 24.64** | 9.30 ± 6.84** | 5.66 ± 3.80** | 71 ± 24** |
| <i>Reference case</i> | 85.14 | - | - | - |

** - Standard deviation – The deviation is used to characterize the results distribution

The TLC strategy will generate the highest demand relief with an average of 16.04 Wh/m² saved. However this strategy has the largest overconsumption after the load control (11.25 Wh/m²). On the other hand the CR strategy will have a lower demand relief but it will have also a lower “payback effect”. Despite the differences between strategies the recovery phenomena seems to be almost the same for the three strategies with value around 75 %, meaning that 75 % of the saved energy during the control will be consumed once the RAC system comes on again.

Although energy effects give us an idea of the quantity of energy consumed, it does not give the load curve effects. Next, figure 5 shows the average consumption for each strategy.

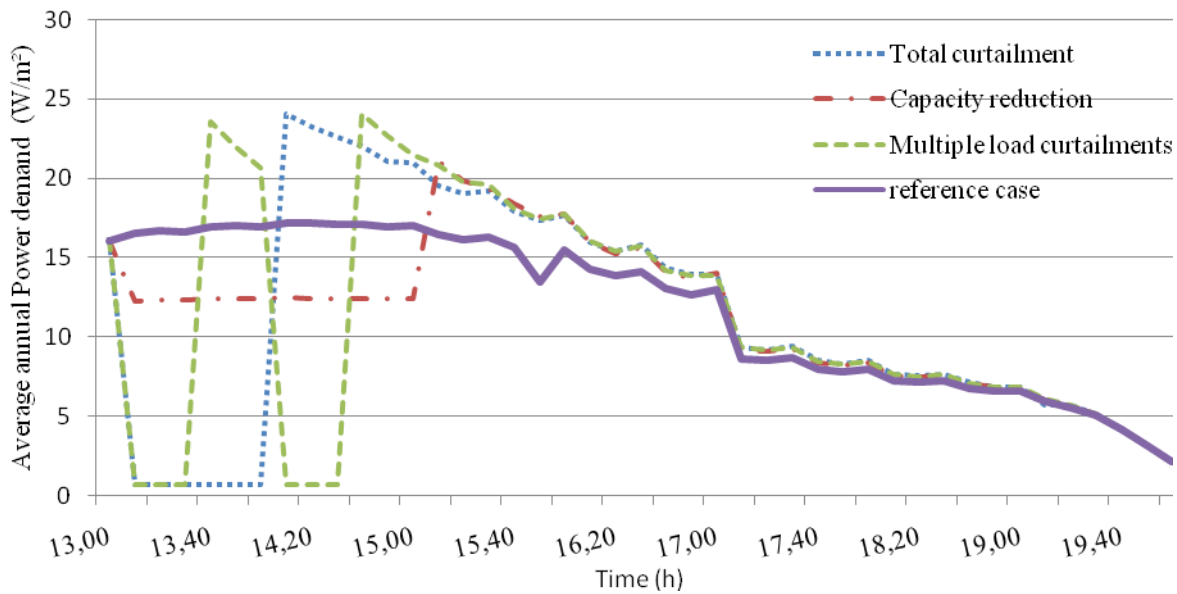


Figure 5 – Average annual consumption for different strategies

In figure 5 it can be seen that the MLC strategy creates two shorter and distinct demands reliefs that the TLC strategy. These peak consumptions are due to the fact that the building got warmer, making the RAC to operate at full load when it restarts. As we get further away from the restart time the over consumption will decrease gradually, so around 17-18h (5-6 p.m) (Figure 4) the consumption curves, for all strategies have almost the same value that for the reference case.

On the Figure 6, we show the avoided power (positive values), during a control, which reaches 16 W/m² for TLC and MLC. After the control period a surplus of power is needed (negative values), and a negative peak of 7 W/m² is created. Despite the CR strategy gives the lowest load reduction (4.5 W/m²), it has also the lowest impact after the control (4.5 W/m²).

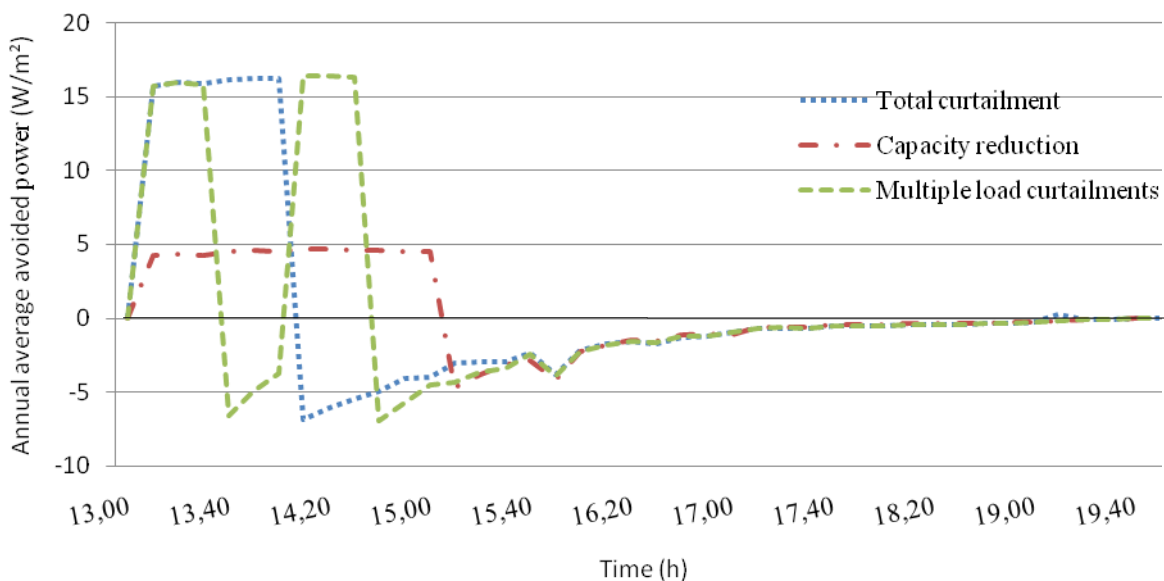


Figure 6 – Average avoided power (difference between strategies and the reference case)

3.2 Comfort in load curtailment condition

In this paper the occupants comfort is analyzed for the room with the highest cooling loads. The following figure gives an example of operative temperature evolution when each strategy is applied and for the reference case.

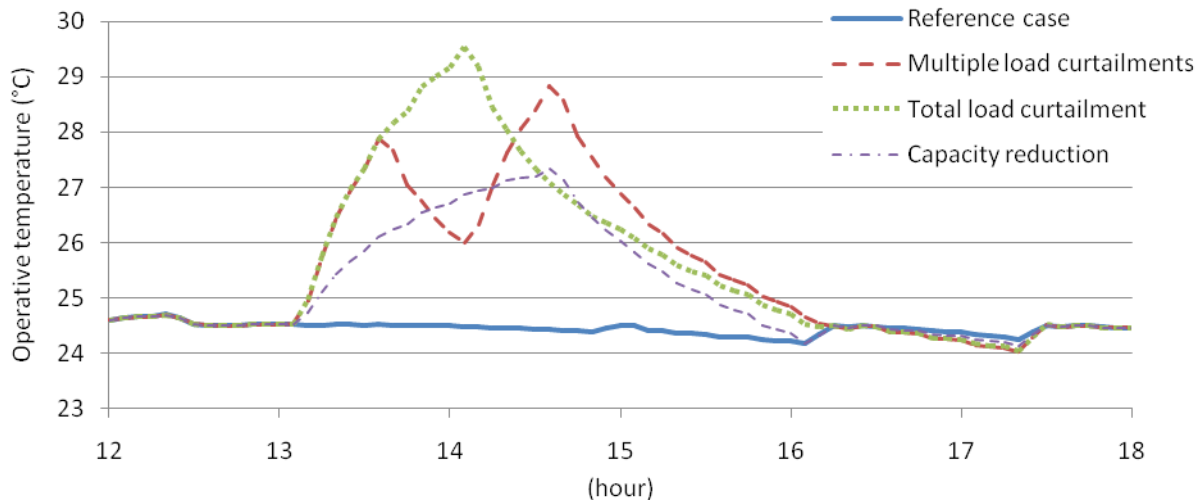


Figure 7 – Operative temperature evolutions for each strategy

It can be seen that with the TLC strategy the temperature reaches the higher temperature peak at almost 30 °C. On the other hand the CR strategy exceeds only by little 27°C, and its time over 27°C is short.

In table 3 we show the comfort impacts of each control strategy for the whole cooling season.

Table 3– Comfort impact for each strategy

| | <i>Total load curtailment (TLC)</i> | <i>Capacity reduction (CR)</i> | <i>Multiple load curtailments (MLC)</i> |
|---|-------------------------------------|--------------------------------|---|
| <i>Non-comfortable days (Top>27°C)</i> | 78 % | 8 % | 52 % |
| <i>Number of minutes per day out of comfort range</i> | 27.66 ± 10.86** | 12.89 ± 9.90** | 22.38 ± 8.34** |
| <i>Annual comfort impact</i> | 39.96 DH* | 2.62 DH* | 9.08 DH* |

** - Standard deviation – The deviation is used to characterize the results distribution

As expected the CR strategy has the lowest impact on occupant’s thermal comfort with the lowest number of minutes per day out of comfort range (12.89 min). Although the TLC and the MLC strategies seem to have the same energetic effects, in terms of comfort impact the MLC strategy has a smaller impact in occupants comfort. The minutes per day out of comfort range for the MLC strategy is only 5 min/day less than for the TLC strategy, but when we compare the degree hours of discomfort, it can be seen that there is a reduction of 75 % when comparing MLC to TLC.

The EN 15251 specifies that a building can be non-comfortable for 5% of its occupation hours per day. In our case the non-comfortable time-period represents 24 minutes, meaning that only the CR strategy offers comfortable figures for this comfort criterion. The MLC strategy despite having an average number of minutes out of comfort range below the comfort criterion limit (24 minutes), it remains very close to the limit and the MLC standard deviation (±8.34 minutes) shows that the comfort criterion will be exceeded very easily.

3.3 Heat Wave

Next we present the results for the energy impacts when load controls are applied during a heat wave, which represent the ten consecutive hottest days for the “Nice- France” climate.

Table 4 - Energy effects for the different control strategies during Heat wave

| | <i>Energy savings</i> [Wh / m ²] | <i>Overconsumption after the control</i> [Wh / m ²] | <i>Recovery</i> [%] |
|--|---|--|------------------------|
| <i>Total curtailment (TLC)</i> | 22.94 ± 0.55** | 12.65 ± 1.73** | 55 ± 7** |
| <i>Multiple load curtailment (MLC)</i> | 22.62 ± 0.56** | 12.32 ± 1.70** | 54 ± 7** |
| <i>Capacity reduction (CR)</i> | 19.34 ± 1.73** | 10.34 ± 1.52** | 53 ± 4** |

** - Standard deviation – The deviation is used to characterize the results distribution

The results in table 4 show that due to higher consumption of the RAC in the reference case (no control), we can achieve larger savings during a control. For TLC and MLC savings around 22.6 Wh/m² can be achieved for this building type. The CR strategy has a similar energy saving when compared with the TLC and the MLC strategies during a heat wave.

The recovery effect has an average value of 55 % for all strategies in a heat wave condition, which is lower than the annual average. The reduction of the recovery effect is explained by the fact that the RAC is almost operating at full-load for the reference case (*Saturated*). When the RAC is restarted only a little surplus of power can be consumed. This feature will harm even more the comfort since the room temperature will decrease slowly, resting this way more time outside of the comfort range (Table 5).

Table 5 - Comfort impact for each strategy during a heat wave

| | <i>Total load curtailment (TLC)</i> | <i>Capacity reduction (CR)</i> | <i>Multiple load curtailments (MLC)</i> |
|---|-------------------------------------|--------------------------------|---|
| <i>Non-comfortable days</i> | 10/10 | 9/10 | 10/10 |
| <i>Time out-of-comfort zone per day (min)</i> | 35.23 ± 4.31** | 26.57 ± 13.45** | 30.42 ± 7.38** |

** - Standard deviation – The deviation is used to characterize the results distribution

The comfort impacts increases significantly when compared with the averages for the all cooling season. In the event of a heat wave no strategy can be considered as comfortable in agreement with EN 15 251.

4. DISCUSSION

The results give a value for the flexibility that can be provided by RAC systems in small French office buildings. Nevertheless this methodology can also be applied to residential buildings, by modifying building characteristics. We consider that the ongoing study will not change strongly the conclusions since the phenomena of air change and conduction through building shell will not be very different according to building types. However special attention should be taken, regarding special building types because they can have different internal gains.

Total load curtailment (TLC) strategy provides the largest demand relief. However large peak consumption is created immediately after the load control. The Multiple Load Curtailments (MLC) strategy presents the same problem, though instead of one single peak consumption, two peaks are

created with the same magnitude. For the electric network this feature can create a problem because the peak consumption is only avoided during a limited time period and when the RAC restarts another peak consumption is created.

On the other hand the CR strategy has a lower peak consumption reduction and a lower peak consumption problem after the load control. With this strategy high current problems caused by the start of the electric motor can be avoided.

The comfort results raise the problem of acceptance by occupants of a load control, which can be a barrier to the deployment of air conditioners load controls. It was seen that only for TLC strategy the time out of comfort range was exceeded, considering our comfort range hypotheses, for the whole cooling season. However MLC strategy has an average time out of comfort very close to the defined comfort limits, its standard deviation shows that the comfort limits can be exceeded very easily.

For load control during a heat wave, it was seen that none of the studied control strategies complies with the comfort ranges. Since the DSM strategies applied during a heat wave are normally emergency strategies, some kind of monetary reward could be suitable. Grignon-Massé (Grignon-Masse, 2010) has developed a methodology to evaluate costs of the discomfort in ambience for office buildings. In his study, he analyzed the working performance decrease as a function of the interior temperature, providing this way a cost to the discomfort. However sociological studies are necessary to define the value of this reward in the residential sector.

Regarding the energy effects during a heat wave, the demand relief will be higher since the RAC systems will operate near the full-load. The energy savings will be more or less identical, around 20 Wh/m², for the three strategies. However the reconstitution is lower than for the average cooling season due to the RAC systems saturation, i.e. during the heat wave the RAC will operate at full-load for the reference case, so when the RAC is restarted only a little surplus of power can be consumed. Because of this feature, over dimensioned systems can increase the recovery problem but decrease also the comfort impact during a control.

5. CONCLUSIONS

In this article a methodology was developed to analyze the energy potential of RAC systems taking into account occupant's comfort. This methodology was applied to a small office buildings representative of the French stock during the whole cooling season.

The results show that a large demand relief can be achieved as high as 16 W/m², during one hour, for TLC and MLC strategies. However important peak consumption and recovery effect will appear after the load control period. This can create a network problem, when several buildings are controlled at the same time, where strategies to avoid cold load pick up² should be taken into account.

CR strategy will have a lower demand relief and less peak consumption, however the reconstitution effect will be almost the same as for the other strategies, remaining around 70 %.

The comfort impacts have shown that as an average during the cooling season only the TLC strategy does not comply with the defined comfort limits. This means that a potential load control can be made without interfering with the occupants comfort.

The analysis during a heat wave has shown that none of the simulated strategies complies with the comfort limits, at that time monetary rewards could be needed to convince the occupants to allow any load control.

² - Cold load pick-up: After a load disturbance on the electric network, the reconnected load will be, in general, higher in size and will have a different behavior than the electric network before the disturbance.

6. PERSPECTIVES

Future works will be made to evaluate other control strategies, and other air conditioner equipments (Chillers, Variable Refrigerant Volume air conditioning units...) which could allow different control strategies. A study about the control limits should also be made, i.e. which is allowed control time without affecting the thermal comfort?

An analysis of a load aggregation for a large number of buildings should be made in order to estimate the impact of each strategy in the electrical network.

These studies could be preceded by a more detailed analysis of the thermal comfort in a room, not analyzing only the average temperature in a room, but taking into account the different local discomfort and other variables like humidity.

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