# 555: SOLAR RADIATION MODELING IMPACT ON CONTROL STRATEGIES DESIGN

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**Abstract**
Advanced control strategies based on shading techniques associated with Hybrid ventilation systems can significantly reduce energy consumption while maintaining good indoor conditions in terms of thermal comfort, indoor air quality, lighting and acoustic comfort. Thus, experimental and numerical reliable design tools are needed to generate guidelines on control strategies and select optimal ones. The work described in this paper studies the influence of an advanced sun patch model on the predicted control strategies performances. A model called HYBCELL and an experimental test cell have been used to carry out simulations in order to test the impact of climate, building architecture and the complexity of solar radiation model on generated guidelines. Solar radiation calculation has been based on a detailed sun patch model. This model also includes the calculation of shades generated by the surrounding masks at the facade, the determination of the sunny parts of glazed areas and their projection on the interior surfaces following the direction of the solar beam. In addition, internal distribution of the short-wave and long-wave radiation integrating multiple reflections, direct retransmission and reflection to the outside has been taken into account.

Keywords: Sun patch, Control strategies, Comfort, Modelling, Energy efficiency

## 1. Introduction

At present, building solar design combined with control strategies for hybrid ventilation and heating systems is a key to saving energy while maintaining good indoor air quality and an acceptable thermal comfort. This is also an efficient way to reduce active cooling in summer.
Previous studies have shown the importance of the sun patch and solar radiation modelling inside building. Some topics such as the dynamic localisation and distribution of solar patch algorithms are very well established and well understood [1] others still are matters of research. In particular, the shortwave radiation processes modelling [2] and the complexity of adopted meshing [3].
An advanced sun patch model allows the localisation, at each step time, of the insolated area of the building taking into account shading caused by its own parts and surrounding environment. Those kinds of models are based on sun and building geometrical considerations and the algorithms are based on mathematical transformations and projections [1,4].

A sun patch model can be coupled to a building model in a different way depending on the topic of the study. Thus, if the objective is to characterize particular phenomena such as local thermal comfort, the sun patch must be coupled with a highly meshed grid for each wall. Otherwise, if the objective is to carry out simulations in order to tune control strategies, the sun patch must be taken into account without inducing additional calculation time. As an example, more than 21000 simulations were needed to tune an advanced ventilation controller [5]. Assuming that each simulation took 45 seconds, the tuning process took 2.4 months using six computers.

The aim of this study is to evaluate the influence of different methods of sun patch integration on the predicted performance of heating, cooling and ventilation control strategies. To begin with, an experimental test cell called HYBCELL [4,6] (see figure 1), was modelled using HYBCELL1.0 simulation tool [4,6] and an advanced sun patch model was developed and coupled to the test cell model and experimentally validated. Then, simple control strategies based on ON-OFF were implemented in the building model. Finally, numerical simulations were carried out and the performances of the tested controllers were assessed using thermal comfort and energy criteria in order to study the impact of the adopted insolation model on the predicted performance of tested controller.

## 2. Internal insolation Models

Four internal insolation models based on sun patch calculation were developed and tested. The difference between them consisted in the way the insolated area for each wall and window was taken into account in the internal shortwave radiation process.

### 2.1 Sun patch calculation

The short-wave radiation calculation was based on a sun patch model [1,7]. This model included the calculation of shades generated by the surrounding masks at the façade and the determination of the sunny parts of glazed areas.
Internal sun patch geometry determination consisted in projecting insolated area of each window onto internal side of simulated room walls

following the direction of the solar beam (see the example of figure 2).

*Fig 1. Hybcell test cell facade*

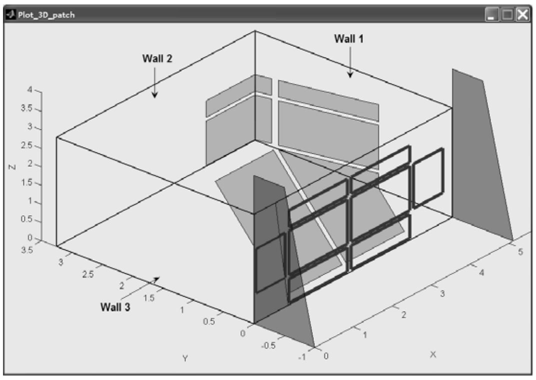


*Fig 2. Example of simulated sun patch for HYBCELL test cell*

Most of classical sun patch models consist in the determination of simple point containment tests applied to a grid superimposed on the target wall (see figure 3 (a) )[1,3]. Thus, the quality of result and the simulation time highly depend on the adopted mesh fineness. In the opposite, the theory proposed in this study uses a dynamic mesh with only two zones for each wall: Insolated and shaded zones (see figure 3 (b)). The four models tested are:

Model 1: Each wall is divided into two dynamic areas according to figure 3 (b) scheme. Thus, HYBCELL1.0 calculated two surface temperatures.

Model 2: Each wall is considered as unique area and the insolation taken into account is as follows:

$$I_{wall} = I_{inc} \cdot \frac{A_{insol}}{A_{Wall}}$$

Were:
$I_{wall}$: Wall insolation [W.m$^{-2}$]
$I_{inc}$ : Direct intensity on the wall [W.m$^{-2}$]
$A_{insol}$ : Wall Insolated area [m²]
$A_{wall}$ : Wall area [m²]

Model 3: Except the floor, all walls are assumed to be shaded. The floor insolation taken into account is as follows:

$$I_{floor} = I_{inc\_floor} \cdot \frac{\sum_{i=1}^{\text{number of walls}} A_{wall,i}}{A_{floor}}$$

Where:
$I_{floor}$: Floor insolation [W.m$^{-2}$]
$I_{inc\_floor}$ : Direct intensity on the floor [W.m$^{-2}$]
$A_{wall,i}$ : Insolated area for wall i [m²]
$A_{floor}$ : Floor area [m²]

Model 4: Except the floor, all walls are assumed to be shaded. The floor insolation taken into account is as follows:

$$I_{floor} = I_{inc\_floor} \cdot \frac{\sum_{i=1}^{\text{number of windows}} A_{win,i}}{A_{floor}}$$

Were:
$A_{win,i}$ : Insolated area for window i [m²]

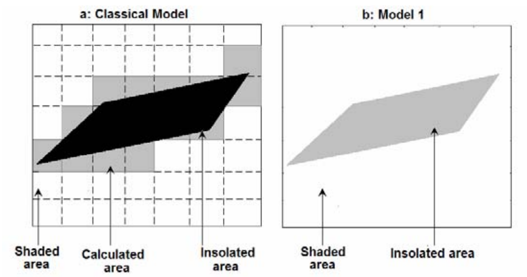


*Fig 3. Classical and Model 1 sun patch models*

**2.2 Shortwave and long wave radiation processes**

To compute the internal distribution of the short-wave radiation used in HYBCELL1.0, multiple reflections, direct retransmission and reflection to the outside were taken into account [2]. Reflection was assumed to be diffuse on the interior surfaces.
Internal net long-wave radiation exchanges were carried out using a radiosity [4] and view factors are based on an area weigh technique as follow:

$$F_{i,j} = \begin{cases} \dfrac{A_j}{\sum_{k \notin \Omega_i}^{N} A_k} & if \quad j \notin \Omega_i \\ 0 \quad if \quad j \in \Omega_i \\ \Omega_i = \quad \text{set of facets located on the wall containing } A_i \end{cases}$$

**2.3 Validation**

Experimental data provided by the HYBCELL test cell were used adjust the sun patch model. Experimental monitoring was led under Lyon (France) winter and summer conditions.
This comparison shows that under winter conditions where insolation flux is characterised by its fluctuation, the sun patch model (Model 1) temperatures agreed well with the measured one, the difference is less than 0.5 °C. The temperature fluctuation is well described by the sun patch model (see figure 4).

Under summer conditions (figure), the difference between simulated and measured temperatures is moderately higher (1°C), but the dynamics of temperature curves are similar (see figure 5).

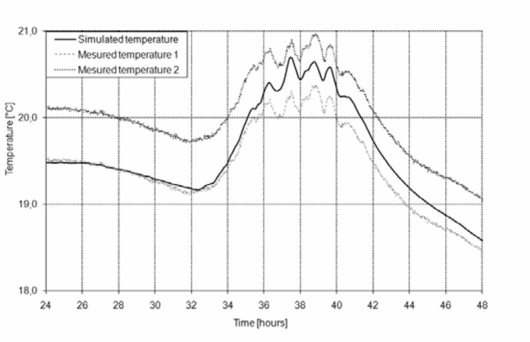


*Fig 4. Model 1 winter validation*

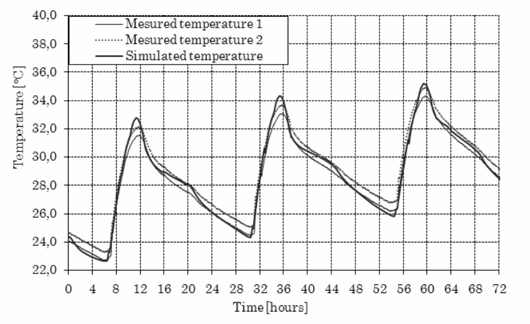


*Fig 5. Model 1 summer validation*

Figure 2 shows an example of sun patch calculation where the shaded part of HYBCELL test cell facade and the insolated parts of windows were projected on the internal side of the test cell enclosure.

## 3. Tested control strategies

Simple control strategies based on ON-OFF controllers for heating (in winter), and active and passive cooling in summer which were developed and tested in the frame work of previous studies [5] were simulated and their performances were assessed according to the sun patch models used (See 2.1).

Winter strategy consisted in combining an ON-OFF heating controller with an indoor air quality controller.

The heating controller has two set points:

- Heating hours (from 7h to 19h): 20 °C
- Non-heating hours (from 19h to 7h): 16 °C

The dead band was set at to 2 °C and the maximum power to 2000 W.

The indoor air quality controller is an ON-OFF one based on $CO_2$ concentration with a set point equal to 900 ppm and a dead band of 200 ppm. When the controller is on, the mechanical ventilation of HYBCELL (3 Vol.$h^{-1}$) is switched on.

Night time summer strategy consisted in night cooling (between 22.00 pm and 6.00 am) using the natural part of the HYBCELL hybrid system. This system is on only if outdoor temperature is 2°C lower than indoor temperature.

Day time summer control strategy combines the winter indoor air quality and an ON-OFF active cooling controller (between 8.00 am and 18.00 pm). The set point of this controller was set at 26 °C with a dead band equal to 2 °C. Maximum cooling power was set at 2000 W.

## 4. Results and discussion

Two periods of one month were simulated: from the 1st to the 31st of January (winter) and from the $19^{th}$ of June to the $18^{th}$ of July (summer). Simulations were carried out using Lyon climate (Lat: 45.8 North, long 4.8 East).

The test cell simulated (HYBCELL) is a single room (5.1m long, 3.2m wide and 2.95m high) oriented 110° Est. Simulations were done both for this orientation and for a virtual test cell having the same dimensions and the same materials but assumed to be oriented South.

The objective was to test the influence of the degree of complexity of the developed sun patch model (Model1, Model2, Model3 and Model4 see 2.1) on the performance of developed control strategies architectures. This influence was assessed varying season, orientation and thermal mass added on the floor. The effect of thermal mass was simulated by adding 10 cm of concrete paving block on the floor.

As an example, table 1 summarizes the simulations done for Model 1 in case of winter season. Thus 32 simulations were carried out for the two seasons and the four models.

Table 1: simulations done for model1 in case of winter season

| Simulation | Orientation | Thermal mass |
|---|---|---|
| W_M1_1 | South | No |
| W_M1_2 | South | Yes |
| W_M1_3 | 110° Est | No |
| W_M1_4 | 110° Est | Yes |

Figure 6 shows the simulated sun patch ratio for the floor, Wall 1, Wall 2 and Wall 3 (see figure 2 to distinguish those walls) according to season and orientation. All comparisons in this study are relative to Model 1

Results showed that the differences between models (Model 1, Model 2, Model 3 and Model 4) highly depend on season and orientation.

The thermal mass induced amplitude differences while conserving the noticed differences.

### 4.1 Models comparison

For winter season and for south orientation (figure 10 and 11) Model 1 and Model 2 agree well while Model 3 calculates higher temperature (2 °C higher) and Model 4 calculates lower temperatures (1.5 °C to 2 °C lower). For East orientation there are no significative temperature differences. During winter season sun altitude is less than 20° therefore and Wall 1, Wall 2 and Wall 3 are more insulated than during summer season and sun patch areas are higher (see figure 6). Under those conditions, Model 3, which

projected all calculated sun patch areas on the floor, overestimates indoor air temperature. Model 4 underestimate calculated indoor air temperature because windows area is lower than are sun patch.
In case of 110° East oriented test cell, winter results did nott return great differences between models (less than 0.3 °C) thanks to the orientation and test cell masks (see figure 2).

For summer simulations, sun altitude is higher and most of the sun patch is on the floor, therefore Model 4 overestimates indoor air temperature, up to 4 °C in case of south orientation with added thermal mass. As for winter simulations, 110° East oriented test cell revealed no differences between models (See figures 7, 8 and 9)

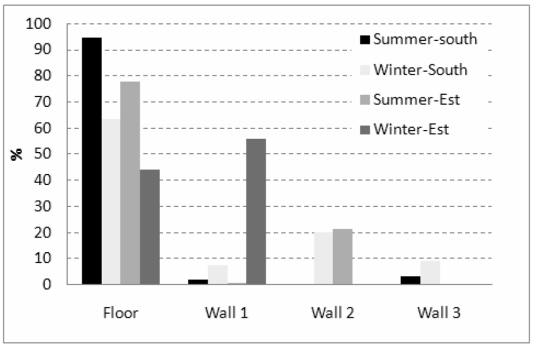


*Fig 6. Sun patch distribution according to season and orientation*

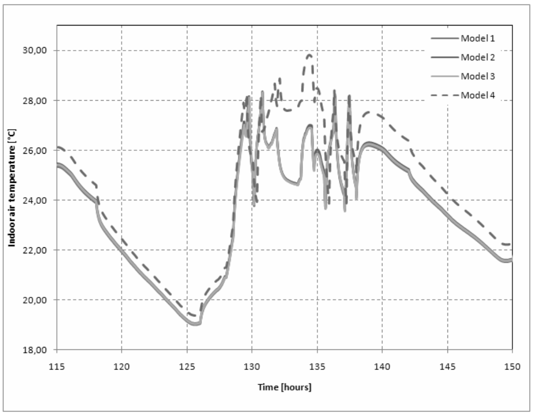


*Fig 7. Example of summer simulated temperature: South orientation with added thermal mass*

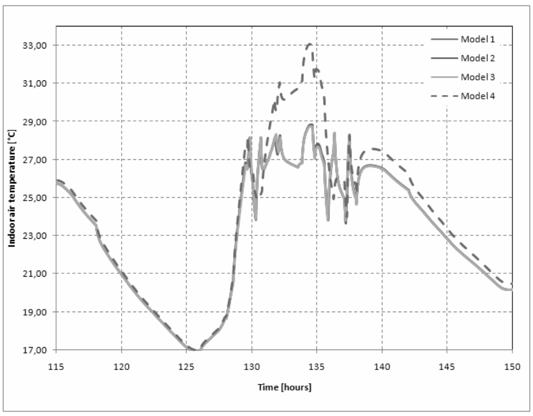


*Fig 8. Example of summer simulated temperature: South orientation without added thermal mass*

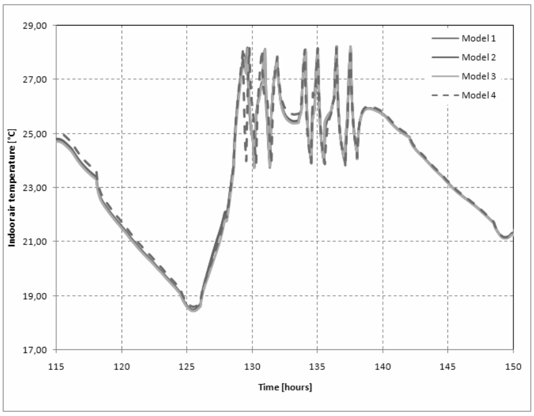


*Fig 9. Example of summer simulated temperature: 110° East orientation with added thermal mass*

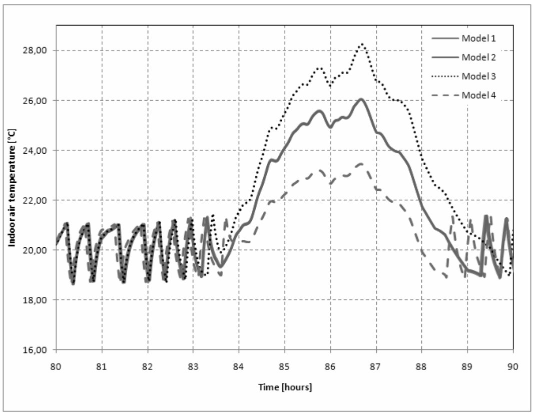


*Fig 10. Example of winter simulated temperature: South orientation with added thermal mass*

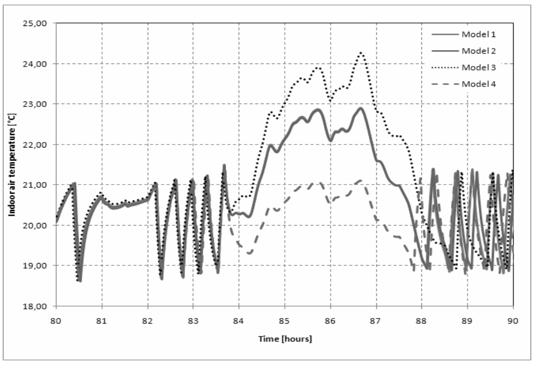


*Fig 11. Example of winter simulated temperature: South orientation without added thermal mass*

### 4.1 Impact on control strategies

Tables 2 and 3 show control strategies performances in terms of heating and active cooling energy consumption. Comparisons are relative to Model 1, assumed to be the more realistic one (see validation part 2.3).
In case of south orientation during summer season Model 4 presentes 8% to 10.5% of overestimated energy consumption, the higher percentage is noticed when thermal mass is added. During winter season, Model 4 still overestimated energy consumption (6%) but thermal mass has very low effect (0.4%). Model 3 (resp. Model 2) underestimated energy consumption -9.17 % (resp. -2.3 %).

Table 2: Energy consumption results (in kWh) in case of south orientation

| Saison | Thermal mass | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|---|
| Summer | Yes | 452.60 | 455.57 | 452.33 | 499.87 |
| Summer | No | 461.60 | 462.43 | 459.17 | 498.17 |
| Winter | Yes | 283.97 | 277.33 | 257.93 | 302.40 |
| Winter | No | 297.93 | 297.80 | 284.83 | 316.23 |

In case of 110° East orientation, with the exception of Model 4 under summer conditions (see table 3) which overestimates energy consumption (9.3 % for added thermal mass and 7.8 % for no thermal mass added), other models and configurations have similar results.

Table 3: Energy consumption results (in kWh) in case of 110° East orientation

| Saison | Thermal mass | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|---|
| Summer | Yes | 279.83 | 281.73 | 278.33 | 305.97 |
| Summer | No | 303.13 | 304.27 | 300.37 | 327.00 |
| Winter | Yes | 388.93 | 388.67 | 387.77 | 386.10 |
| Winter | No | 385.90 | 385.63 | 384.97 | 383.17 |

## 4. Conclusion

In this study, a sun patch calculation algorithm was integrated to HYBCEL software and four internal shortwave models were developed and their thermal performances in terms of indoor air temperature were compared. In addition, their impact on simple control strategies based on ON-OFF controller for heating, ventilating and air conditioning in terms of energy consumption was studied.

Results show that the degree of differences between models concerning simulated indoor air temperature and energy consumption highly depends on orientation, season and thermal mass. Therefore, extra care has to be taken when modelling sun patch and internal shortwave radiation in order to design control strategies. In fact, generated guidelines using certain tested models under specific configurations may induce up to 10% over or underestimation of energy consumption and 0.5 °C up to 4 °C difference concerning thermal comfort. Table 4 summarizes lessons learned and gives some recommendations about which model to use (compared to Model 1) in order to prevent design errors

Table 4: Recommendations for design

| Model | Temperature | Energy |
|---|---|---|
| Model 2 | Recommended for all tested configurations | Avoid winter season with thermal mass |
| Model 3 | Avoid winter season and south orientation risk of overestimation | Avoid winter season |
| Model 4 | Under and overestimations, except for winter East orientation | Suitable for only East orientation in winter |

Further studies will focus on the impact of developed models on advanced control strategies (PID and Fuzzy logic architectures); also, we will carry out additional parametric studies including location (Rome and Copenhagen), materials (reflection, transmission, emissivity, ...) will be carried out.

## 7. References


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