Evaporative Cooling and Ventilation Control Strategies for a Kindergarten in Mediterranean Climate

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ABSTRACT

Aim of this work has been to determine the effectiveness of evaporative cooling and ventilation control strategies on a case study to ensure an adequate combination between energy efficiency and high levels of indoor comfort.
The case study has been a kindergarten, situated in the context of the climate continental Mediterranean area (Cerignola, Italy, 41°16'00"N, 15°54'00"E, 120 m asl), oriented on an east/west axis, classrooms south faced, and the services zone to north.
Several strategies for passive and hybrid cooling of the classrooms have been simulated in order to reduce the overheating in the summer season and to reach high levels of air quality.
Different solutions have been simulated to evaluate the optimum operative conditions, through the TRNSYS simulation software.
The first design strategy have regarded a night hybrid ventilation (from 10 p.m to 6 a.m.). The thermal comfort analysis, according to the adaptive thermal comfort (EN 15251-2007), have shown the reduction of overheating and the need to introduce a control logic, in relation to the outdoor temperature, to reduce the undercooling in the early hours of occupancy.
It has been necessary to provide a ventilative cooling strategy also during daytime in order to obtain a significant reduction of overheating.
The second design strategy has involved the adoption of a direct evaporative cooling system. The simulation have concerned different combinations of evaporation efficiency and air flow rates. The results have shown the optimal air flow rate for different evaporation efficiencies. Analysis on relative humidity levels have shown that the evaporative cooling system did not significantly alter the levels of relative humidity and there was a positive increase in the minimum levels of relative humidity.
This study have underlined that passive cooling systems, operated by a suitable control logic, can provide performance levels almost comparable with those of an air conditioning system, ensuring a significant reduction of energy consumption.

KEYWORDS

Natural ventilation, thermal comfort, passive cooling, evaporative cooling, building automation

1 INTRODUCTION

The increased usage of air conditioning systems in buildings has caused an higher energy consumption, an increase in peak electricity demand and significant environmental impact such as global warming and ozone depletion (M. Santamouris, 2007).
As a result, the recovery of natural techniques of cooling can be sufficient to restore conditions comfort inside buildings, reducing or eliminating the use of conventional mechanical cooling systems.
Passive cooling systems are one of the well-known strategies that can maintaining indoor comfort reducing energy consumption related to space cooling. Generally, these strategies

consist in the solar heat gains control and in the internal heat gains reduction by altering building envelope elements. Some passive cooling strategies aim at lowering the indoor temperatures by utilizing natural heat sinks such as ambient air, sky, ground, and water (B. Givoni, 2011).

Natural ventilation is considered one of the most effective passive cooling techniques to reduce energy consumption of buildings and improve indoor air quality.

There were few studies, especially experimental work, that have evaluated the potential of passive cooling techniques in hot climates. For example, Bajwa (Bajwa, 1993) et al. have investigated the effectiveness of passive **evaporative cooling techniques** through experiments on two-story full-scale test house in the eastern region of Saudi Arabia.

Passive evaporative cooling is typically suitable for hot and dry climates. The passive cooling system is able to cool the indoor spaces with minimal use of energy (Alaidroos, 2015).

In this paper two passive cooling techniques have been evaluated including natural ventilation systems, in particular night cooling ventilation, and an evaporative cooling system, as retrofit solutions to improve thermal comfort in a kindergarten located in a rural zone of the Southern Italy.

2 METHODOLOGY AND PHASES OF THE WORK

This study has focused on evaporative cooling and ventilation control strategies to achieve high levels of energy efficiency and indoor comfort during summer period for a kindergarten located in Cerignola (Italy- Apulia).

In the first phase building thermal and visual performances have been evaluated to identify the zones with worse conditions, through the software Ecotect (Autodesk). Thermal comfort analysis have been conducted according to the standard UNI EN 15251. This standard defines an upper and lower comfort temperature related to the external conditions.

In particular, relatively to the occupation hours, the discomfort due to overheating and undercooling has been calculated, in reference to the upper and lower temperature limit.

The analyses focused on the southern building part, where the classrooms are located, that are characterized by the higher percentage of indoor thermal discomfort.

In the second phase, the thermal model has been implemented within the TRNSYS software and different design solutions are simulated for energy savings and for improve thermal comfort conditions. At first, ventilation control strategies has been hypothesized due to high thermal loads and the high levels of Indoor Air Quality (IAQ) required for kindergartens. A night-hybrid ventilation has been simulated for the building, occupied only in the daytime and with high inertia of the opaque components such as the roof slab.

Despite the benefits from the night ventilation system, it has been necessary to provide a more efficient cooling strategy under daytime. An evaporative cooling system has been chosen due to the high external air temperatures and due to the low external relative humidity. Several evaporative cooling strategies were simulated by varying the characteristic parameters such as efficiency and air flow rates.

Finally, regarding the optimal design of the evaporative cooling system, internal relative humidity levels were checked to assess whether they were acceptable.

3. CASE STUDY

The case study has regarded an existing kindergarten (under completion), situated in a rural context of Cerignola (southern Italy).

It is subdivided in three sections (baby aged 3-12 months, 12-24 months, 24-36 months), each articulated in classrooms, quiet rooms, play activities room and services area.

The building has one basement and one floor above ground, 6 meters high, floor area of about 795 m^2 and green zone of 1100 m^2. It is characterized by (fig.1):

- windowed sides facing to south (classrooms) and to north small (services area);
- compactness index (ratio between enveloping surface and heated volume) equal to 0.64, as result of the building type;
- an overhang to south that shields the window areas (fig.2);
- a horizontal skylight placed on ceiling of classrooms.

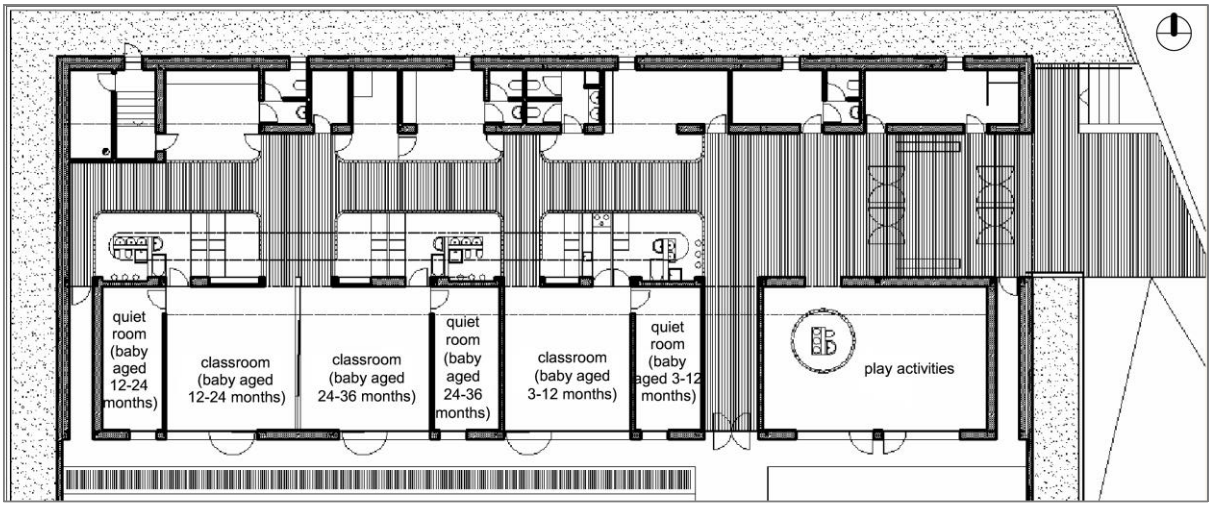

Figure 1: Ground floor plan

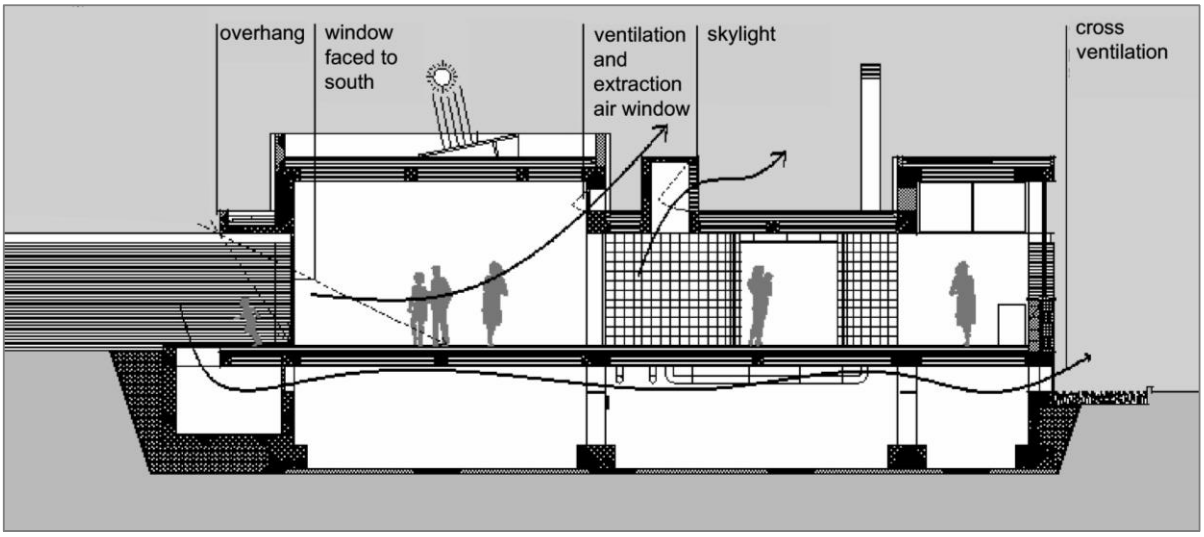

Figure 2: Sections of the building

Thermal characteristics of the building envelope are shown in the following table (tab.1):

Table 1: Thermal characterstics of the envelopes

Items	Thickness (cm)	U-value ($W/m^2 K$)	Thermal lag (hr)
External northern wall	57,5	0,37	18,7
External southern wall	41,5	0,39	12,5
Roof	45,0	0,46	13,1
Ground floor	38,5	0,48	11,8
Window	4-12-4	2,90	-

As regard the HVAC systems, there is no cooling systems or mechanical ventilation plants.

3.1 Internal Thermal Loads of the Building Model

In order to consider the *internal heat gains* for occupancy, lighting and equipment, several typical schedules have been implemented in the TRNSYS software. In particular, according to Edyth Boyd (E. Boyd, 1935), the internal heat gains (IHG) due to the baby has been estimated on height, weight and body surface area (BSA):

$$BSA\ (m^2) = 0{,}0003207 * height\ (cm)^{0,3} * weight\ (gr)^{(0,7285 - (0,0188*LOGweight(gr))} \quad (1)$$

$$IHG\ (w) = metabolic\ rate * BSA \quad (2)$$

For determine height and weight data of babies, reference was made to the anthropometric data provided by medical studies, particularly those of Tanner, Whitehouse and Takashi.
The metabolic rate has been estimated according to ISO 7730:2005 for kindergartens.
The following table summarizes the thermal loads determined by each occupant in relation to the type of activity.

Table 2: Internal Heat Gains

User	**Height (mt)**	**Weight (kg)**	**B.S.A. (m^2)**	**Activity**	**Metabolic rate (W/m^2)**	**I.H.G. (W)**	**Sensible I.H.G. (60%) (W)**	**Latent I.H.G. (40%) (W)**
Baby aged 3-12 months	0,67	7,65	0,39	classroom	81	32,16	19,30	12,86
				quiet room	66	26,20	15,72	10,48
Baby aged 12-24 months	0,81	11,35	0,53	classroom	81	42,93	25,76	17,17
				quiet room	66	34,98	20,99	13,99
Baby aged 24-36 months	0,89	13,5	0,60	classroom	81	48,76	29,26	19,50
				quiet room	66	39,73	23,84	15,89
Teacher	1,70	60,0	1,60	classroom	93	148,80	89,28	59,52

The profiles of occupation (fig.3) in the various rooms are determined according to other studies present in literature and to the data provided by teachers.

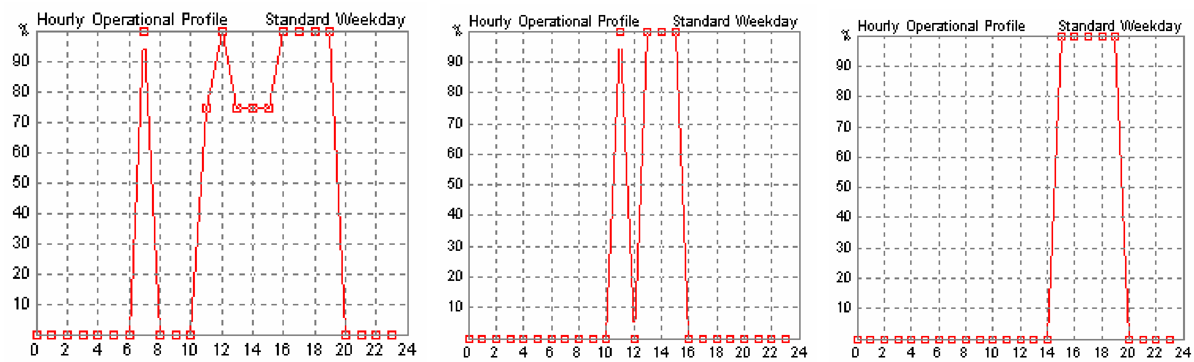

Figure 3: Hourly profile of occupation (classroom, quiet room, common space for recreational activities)

The three classrooms (for babies aged 3-12, 12-24 and 24-36 months) are attended at most by 10 and 20 babies respectively. The common space for recreational activities can host at most 8 babies.

For estimating thermal loads due to *lighting*, high efficiency fluorescent tube have been hypothesized with switching on from 5 p.m. to 7 p.m.
Regarding *ventilation* and *infiltration*, air changes have been defined equal to 0.004 m3/s*person, as defined by the UNI 10339: 1995, and a constant infiltration of 0,5 ACH.

4 CONTROL STRATEGIES FOR VENTILATIVE COOLING

Through the Ecotect software, a thermal-loads analysis of the building and their impact was carried out to identify the most critical elements of the project and provide suitable alternative solutions.
The analysis of heat flows and the internal operating temperatures have shown that the daytime heat gains, responsible of rising temperatures themselves, remained stored within the environment.
It resulted as high levels of discomfort are reached in the classrooms (above all the classroom of baby aged 24-36 months). Indeed this room is characterized by maximum number of occupants, equal to 20, and thermal loads greater for effect of a larger "body surface area", as previously described.
So in this paper cooling strategies for passive ventilation were deepened, evaluating different control logics of the external air flows. For the classroom cited before, several control strategies for ventilative cooling have been analyzed. The strategies and design solutions have been simulated in TRNSYS, Transient SYstem Simulation tool, that performs transient systems analysis using a modular approach able to model most of the envelope and HVAC subsystems (TRNSYS 16, 2004).

4.1 Night Cooling Ventilation System

The first design solution has regarded the adoption of a night cooling ventilation system. For this design strategy there are no limits of flow rate, speed and temperature of the inlet air, due to the absence of users.
A direct hybrid ventilation has been hypothesized, with the inlet openings on the south walls, arranged close to the ceiling with entry assisted by mechanical ventilation (helical ventilator) and extraction for stack effect through the window at the top of the north face.
It was therefore a horizontal ventilation crossing the building, with inlet and air outlet openings placed on opposite walls with incidence of the wind on the plane of the openings and pressure difference between the two openings.
Several simulations are conducted varying the air change flow rate between 2 ACH and 15 ACH in order to obtain the optimal value.
The mechanical ventilation for night cooling was controlled by an internal and external thermostat.
A first activation logic of the ventilator and the window opening will occur when (Case 1):

- time period: 10 p.m. – 6 a.m.
- external temperatures < internal temperatures.

After, in order to reduce the discomfort for undercooling, the activation logic has been implemented as (Case 2):

- time period: 10 p.m. – 6 a.m.
- lower limit temperatures (evaluated according UNI EN 15251) < external temperatures < internal temperatures.

The discussion of the results of these assumptions are reported in the paragraph 4.3, noting that the night-cooling improves but does not solve overheating discomfort.

4.2 Evaporative Cooling System

As underlined in the following paragraph, it resulted the need to integrate the night cooling with a passive cooling during daytime. For the hot-dry climate, typical of the Mediterranean continental climate, during daytime the design solution has concerned on evaporative cooling system. Indeed this cooling is more sensitive if the air is able to make evaporate much water, namely the more the air is dry initially.

During evaporative cooling, the air undergoes a process of humidification and cooling. In energy balance, the reduction of the air temperature does not involve a variation of the enthalpy content of the air. It is an adiabatic cooling where the reduction of air temperature is compensated with the increase of water steam.

Evaporative cooling can be considered, therefore, a process of passive cooling, where the effect of the evaporation of water present in the air is used as natural heat sink (Alaidroos, 2015).

In this paper, a direct evaporative cooling system has been simulated, where the air comes in contact with water and increases RH.

Effectiveness and benefits of such cooling system are function of two parameters:

- efficiency-of evaporation (percentage of saturation);
- airflow rate.

Regarding the efficiency, several simulations have been conducted considering as reference values 30%, 50% and 70%.

For the classroom above analyzed, the air flow has been varied between a minimum value of 2.15 ACH (according UNI 10339 that defines 0.004 m3/s*person) and a maximum value of 13 ACH (by evaluating a maximum velocity of 0.11 m/s according ISO 7730:2005 for Kindergarten). In particular, five air flow rates have been considered: 2,16 ACH, 5 ACH, 7,5 ACH, 10 ACH and 13 ACH.

Different combinations of air flow and efficiency were evaluated during the occupation hours 7:00 am-7:00 p.m, to assess the benefits obtained from the evaporative cooling system by varying the two fundamental parameters and to identify an optimized solution.

In a first set of simulations (obtained combined the three air flow rates with the five efficiency values), the cooling system operated if the inlet temperature was lower than the indoor temperature.

Subsequently in other simulations (obtained combined the air flow rates upper than 5 ACH with the efficiency values greater than 50%), in order to reduce the discomfort for undercooling, the system turned on if:

- indoor operative temperature > optimal temperature;
- inlet temperature < indoor temperature.

4.3 Results

As regarding the **night cooling ventilation system**, the two cases proposed have been compared in terms of adaptive thermal comfort (UNI EN 15251).

The simulations results have shown the efficacy of the proposed ventilative cooling strategies, determining a significant reduction of overheating during the occupation hours. Comparing the Case 0 and Case 1, there was a decrease of overheating discomfort hours of about 30 %, but an increase of undercooling discomfort hours. Therefore, the activation logic of the Case 2 had needed to reduce the undercooling hours without excessively limiting the cooling efficiency of the system.

Table 3: Thermal Comfort Analysis

Case	Overheating discomfort (hr)	Overheating discomfort (degree hours)	Undercooling discomfort (hr)	Undercooling discomfort (d.h.)
Case 0	385	1040	19	21
Case 1	260	483	74	140
Case 2	347	666	28	24

In order to reduce even more the thermal discomfort conditions, by operating also during daytime, the first set of **evaporative cooling system** proposed have underlined as (fig.4) :

- by increasing the air flow rate with equal efficiency, the benefits were lower than those obtainable by increasing efficiency at equal flow;
- for a very low efficiency, inferior to 50%, even at high flow rates the overheating discomforts were considerable, ie the increase of flow was not sufficient to compensate the low efficiency of the system;
- the optimal air flow rate was between 5 ACH and 7 ACH: the slope was maxim before 5 ACH and almost constant after 7 ACH.

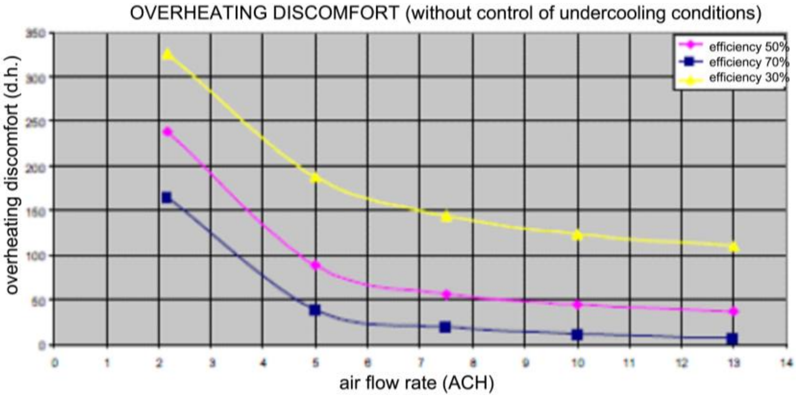

Figure 4: Thermal Comfort Analysis in regime of constant activation

The other set of **evaporative cooling system** proposed have shown as (fig.5) :

- with a greater system efficiency (70%) the operating temperatures had a daily fluctuation mostly contained within the band of comfort;
- high air flow rates, even at high efficiency, were not sufficient to total elimination of overheating discomfort and caused more discomfort conditions for undercooling;
- the optimal solution was represented by 7.5 ACH and efficiency equal to 70%, where occurred only 60 degree hours of discomfort for overheating and undercooling.

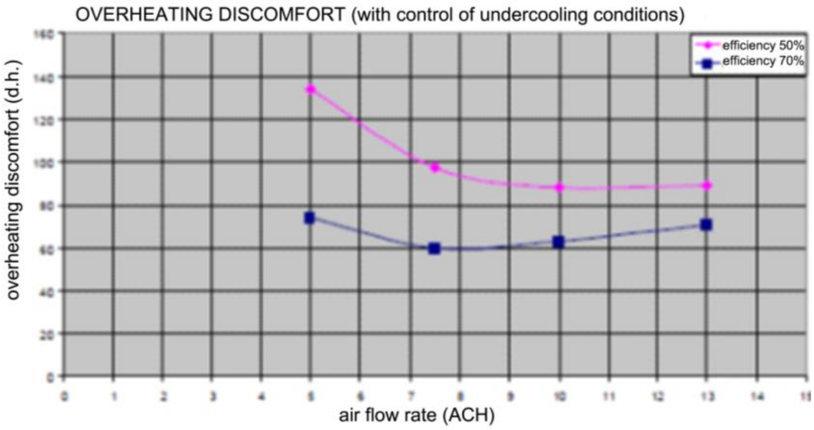

Figure 5: Thermal Comfort Analysis with control logic

The combination of natural cooling ventilation and evaporative cooling system, with control logics above examined, caused a significant reductions of discomfort conditions (> 80%) respect to base case.

Table 4: Thermal Comfort Analysis

Case	Overheating discomfort (hr)	Degree hours for overheating discomfort (d.h.)	Undercooling discomfort (hr)	Degree hours for undercooling discomfort (d.h.)	Total discomfort hours (hr)
Case 0	385	1040	19	21	404
Optimal Case	28	22	48	38	76

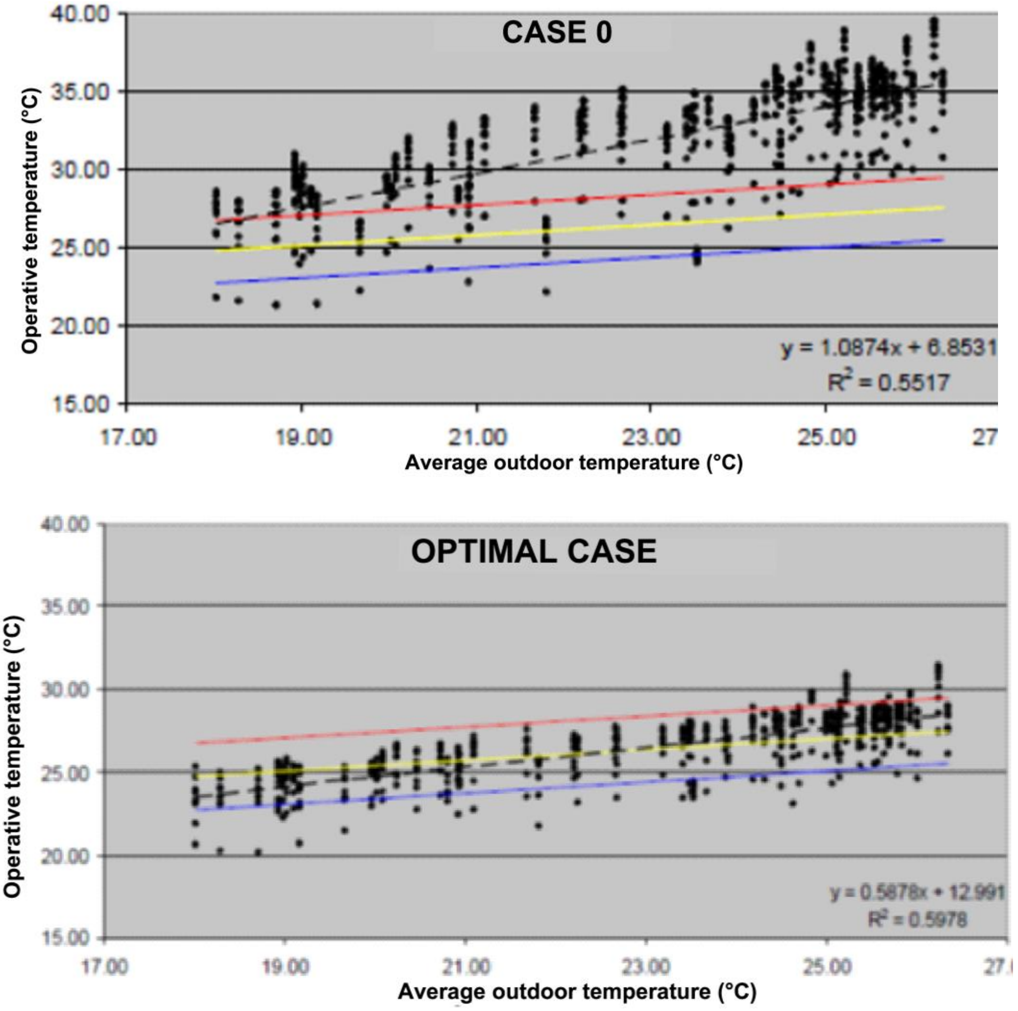

Figure 6: Thermal Comfort Analysis (CASE 0 – OPTIMAL CASE)

Finally, the comparison between the conditions of internal relative humidity in the absence and in the presence of evaporative cooling system was carried out. It is possible to note that the evaporative cooling system:

- did not alter the levels of comfort to a relative humidity internal;
- determined a positive increase in the minimum levels of relative humidity (on hot days and muggy), reducing of the hours when the level of internal humidity was lower than 30%;
- has caused a rise of maximum levels of relative humidity above 70%, however, limited to 5% of the total occupation hours.

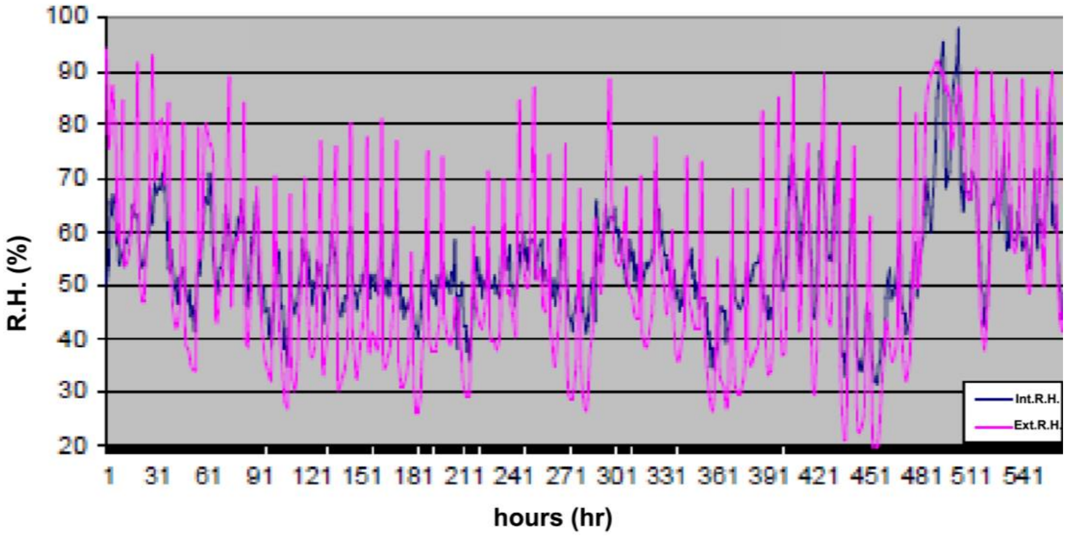

Figure 7: Relative Humidity

Table 5: Analysis of relative humidity levels

Case	40%<R.H.<60%	30%<R.H.<70%	R.H.<30% - R.H.>70%	R.H.<30%	R.H.>70%
Case 0	414 hr	544 hr	23 hr	8 hr	15 hr
	73%	96%	4%	1%	3%
Case optimal	409 hr	536 hr	31 hr	0 hr	31 hr
	72 %	95%	5%	0%	5 %

5 CONCLUSIONS

In this paper evaporative cooling system and ventilation control strategies has been studied to ensure an adequate combination between energy efficiency and high levels of indoor comfort for an existing kindergarten in Mediterranean climate.

The simulations have shown the effectiveness of the night cooling ventilation, particularly in climates with high daily thermal oscillation. Through the control logics described above, it was possible to calibrate the ventilation in relation to the cooling needs, greatly reducing the discomfort for undercooling. Despite the benefits of the night cooling ventilation, a cooling strategy daytime was necessary.

The different strategies for evaporative cooling, obtained by varying the characteristic parameters such as efficiency and flow rate, have shown how it is possible to obtain a high comfort level by adopting reduced flow, if the system has high efficiency.

The analysis showed that the evaporative cooling does not significantly alter the comfort levels for indoor relative humidity. The indoor relative humidity is maintained in the optimal intervals generally 40-60%, and moreover there is a positive increase in the minimum levels of relative humidity.

This study have underlined that passive cooling systems, operated by a suitable control logic, can provide performance levels almost comparable with those of an air conditioning system, ensuring a significant reduction of energy consumption.

6 REFERENCES

M. Santamouris, *Advances In Passive Cooling*. 2007.

B. Givoni, "Indoor temperature reduction by passive cooling systems," Sol. Energy, vol. 85, no. 8, pp. 1692–1726, Aug. 2011.

Willmert, T. (2001). *The return of natural ventilation.* Architectural Record, 189 (7), 137-146.

M. Bajwa, E. Aksugur, and G. Al-Otaibi, (1993) "The Potential of the Evaporative Cooling Techniques in the Gulf Region of the Kingdom of Saudi Arabia," Renew. Energy, vol.3, no. 1, pp. 15–29.

A. Alaidroos, M. Krarti, (2015), *"Impact of passive cooling strategies on energy consumption reduction of residential buildings in the kingdom of Saudi Arabia"*, ASME 2015 9th International Conference on Energy Sustainability, San Diego, California.

Boyd E., (1935), "The growth of the surface area of the human body", Minneapolis: University of Minnesota Press.

UNI 10339:1995, *Air-conditioning systems for thermal comfort in buildings – General, classification and requirements – Offer,order and supply specifications.*

ISO 7730:2005, *Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*

TRNSYS 16 (2004) Volume 05 – Mathematical Reference.

UNI EN 15251 (2007). *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.*