Integration of hybrid ventilation systems in educational buildings

L. Guardigli
Dept. of Architecture and Planning, University of Bologna

M. T. Cascella
Dept. of Mechanical Engineering, University of Bologna

ABSTRACT

The case study of a nursery school of Bologna is a pilot example of how hybrid ventilation systems can be embedded in architecturally significant buildings. This paper has investigated the operating condition of this peculiar design to make sure that design hypothesis were accomplished. To do this, after an overview of local climatic conditions and sensors recent data, a CFD simulation has been made to compare theoretical and real behavior.

1. INTRODUCTION

Hybrid ventilation systems can be described as two-mode systems using different features of both passive and mechanical systems at different times of the day or season. Generally, they take advantage of natural ventilation when it is available and supplement it as necessary with mechanical ventilation.

The challenge is to do this in an energy-efficient way while avoiding the typical disadvantages of natural ventilation – cold drafts and excessive ventilation in winter and inadequate ventilation in summer and shoulder seasons –. The performance of a hybrid ventilation system depends, in fact, on the climate. While there are many doubts about the efficiency of natural ventilation, it is probably correct to think that the biggest advantages of these systems are the potentialities of the architectural space.

The object of this study is to analyze the potential of a specific hybrid ventilation system given the climate characteristics and the innovative architectural space.

Experience and analysis have demonstrated that natural ventilation allows building cooling as long as internal temperature remains inferior than outside temperature; after that, only the air quality renewal is possible due to the heating of the solar stack.

2. CASE STUDY IN BOLOGNA

There are some new cases of sustainable schools with bioclimatic approaches in the region Emilia-Romagna, Italy. However, only a few of them have adopted hybrid ventilation as a strategy for energy efficiency.

We take in consideration here a nursery school near Bologna (Figure 1). This can be considered a "low energy" building thanks to a good insulation. The calculated primary energy consumption (heating system and hot water) per year in cold seasons is 47 KWh/m^2.

Nevertheless, the project is particularly interesting for its architectonic quality; the composition of volumes, exhaust chimneys and glazed south façades protected by sun shields were considered elements of great interest as evidenced in major Italian magazines (Casabella, n. 755).

2.1 Climatic profile

The climatic profile of Bologna is generally characterized by hot summers and severe winters; thermal inversions mitigate the intrusions of polar and arctic masses.

The classification of the Italian national territory into climatic zones puts Bologna in zone E, the second coldest one: in this zone, degree-days range from over 2100 to 3000. The degree-day is the unit used to assign a climatic zone to each municipality and assign a period when the heating system can be turned on; here it is 14 hours/day in the period between October 15th and April 15$^{th.}$

Figure 1. Aerial view of school from SW

Other climatic data for Bologna are reported in Table 1 and Table 2, referred to the hottest months.

Temperature SMR data				Relative humidity Military Aeronautical data
Month	Min Temp. (mean)	Max Temp. (mean)	Mean Temp.	Relative humidity
April	7,8	17,6	12,7	71
May	11,9	22,4	17,2	69
June	15,6	26,7	21,1	68
July	17,7	29,8	23,7	65
August	17,4	29,2	23,3	66
September	14,5	25,2	19,8	69

Table 1. Temperature and humidity values

Global daily radiation on vertical surface variously orientated in MJ/m^2 for Bologna [UNI 10349:1994 Climatic Data]						
Month	S	SO/SE	E/O	NO/NE	N	Horiz.
April	11,2	12,6	11,9	8,5	5,5	5,8
May	10,2	12,7	13,8	11,1	7,9	7,4
June	10	13,1	15,2	12,8	9,7	8,5
July	11,1	14,7	16,8	13,6	9,5	9,4
August	12	14,3	14,3	10,5	6,6	8,4
September	12,9	13,1	11,1	7	4,3	6,7

Table 2. Solar radiation values

2.2 Functional analysis

The envelope of each of the three sections is characterized by a double-skin façade and a set of chimneys for the stack effect.
Natural ventilation is given by a combination of stack effect and cross ventilation; mechanical ventilation is provided by fans when natural ventilation is considered inadequate. A double-skin south oriented façade is a key element of the system: this element, protected by electrically controlled sunscreens, is mainly intended for passive solar heating. If highly radiated, it could reduce the stack effect which is determined by the temperature gradient between the internal air and the pre-heated internal air of the cavity of the façade.
The effect can be potentially activated by the depression of the lee side of the chimney in case of wind, but this case is quite rare, given the average wind speed in Bologna of 1,6 m/s, with direction NW (UNI 10349).
Moreover, the aluminum chimney heats up the internal air, contributing to the temperature gradient. Therefore, different mechanisms can be activated depending on the use of the "intelligent façade", constituted by a 10mm tempered glass, a 450mm cavity with venetian blinds and a double glass 8/9-15-8/9 inside (U-value of 1.5 W/m^2/K). All that has been given design consideration and sometimes natural ventilation is helped with mechanical one.
The façade has three sets of louvers. Ventilation inlet louvers SA are placed at the floor level. During the summer the air is extracted vertically from the cavity by louver SC. In winter one outlet louver SB is placed in the cavity at the ceiling level to allow the pre-heated air to enter the classroom in cold months.
A teacher and 25 pupils are assumed to be in the two rooms of each section from 8:00 to 12:00 and from 13:00 to 15:00 on Mondays to Fridays.
The internal heat gains can be assumed 10 W/m^2 for lighting and 80 W per person; CO_2 production was 18 l/h per person.
According to Italian regulations, in nursery schools the required flow rate is $4*10^{-3}$ m^3/s per person in classrooms, which is equivalent to 14 m^3/h per person.

Figure 2. Image of the simulated part of the school

In bathrooms 8 vol/h are granted by an extractor controlled by a temporized sensor;
In the lunchroom there is an air flow automatic control system in relation to the real number of attending people; maximum is set to 90 people (UNI 10339). What is noteworthy is the behavior of the hybrid system in the classrooms, where three situations take place:

a) Colder period natural ventilation

During the coldest months the "intelligent façade" enables pre-heating of the renovation air inside the cavity; this one usually reaches higher values than indoor air, up to 30°C (Figure 3).
The position of the bathroom in each section, very close to the façade, helps passive heat gain from radiation creating a sort of greenhouse.

b) Warmer Period natural ventilation

Natural cross ventilation is actuated mainly at night according to the scheme in figure 3.
Cross ventilation is favored by small openings in the north façade which start the transversal movement. An additional water cooling system on the roof gives another contribute.
During the day solar shading is provided whenever the total incident solar radiation is higher than 200 W/m^2. Radiation is also reduced through venetian blinds placed inside the cavity.
If the temperature is too high, air in the cavity is extracted from the top of the cavity over the roof level by the louver SC. Mechanical ventilation starts when the microclimatic conditions are such that natural ventilation is considered not sufficient.

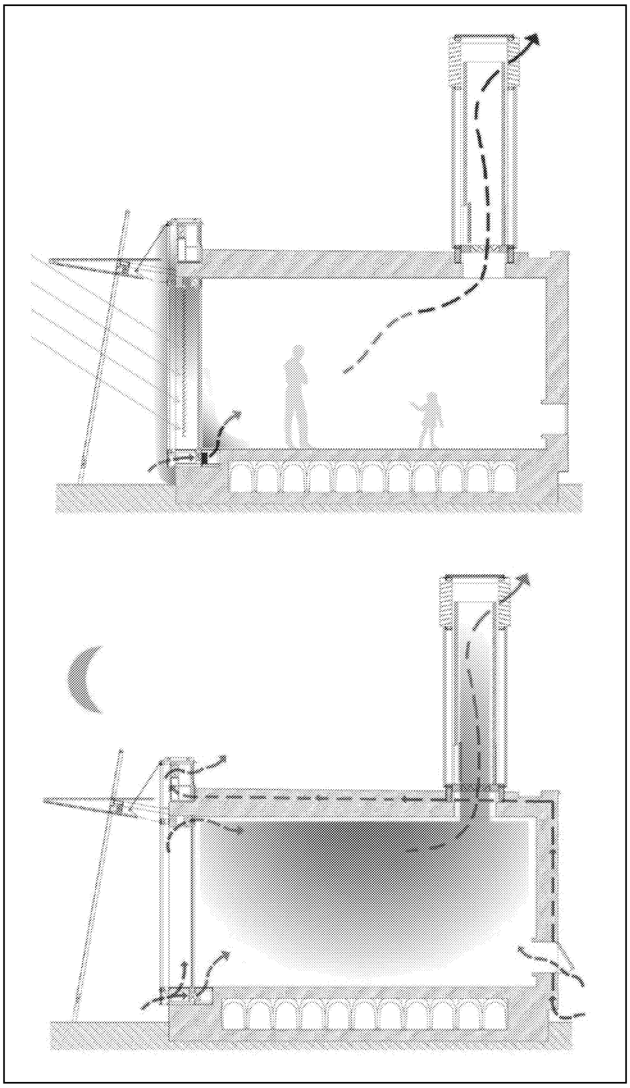

Figure 3. Cold season day and warm season night

c) Ventilation for air quality

The inlet and outlet opening control is not only dependent on the ventilation hours, but also on indoor CO_2 concentration, which is a top priority among all other combinations. The ventilation is regulated by an air quality sensor (SQA) which extracts the air re-establishing the standard values of CO_2. The renovated air is preheated through a thermal exchanger that absorbs the heat of the exhaust air. Air temperature is analyzed and, if it doesn't reach the minimum required level of 22°C, is raised by the finned pipe.
Air extraction is placed in the "plenum" of the bathrooms, through a connected set of grilles inserted in the doors separating them from teachers room and locker rooms.

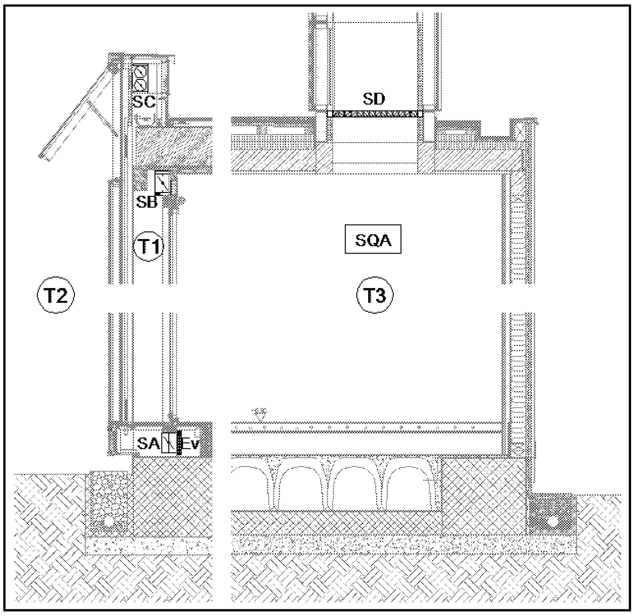

Figure 4. Room section

The exhaust air is forcely extracted and reintegrated by the air passing through the façade. The extraction is managed by a “presence” sensor.
The louver opens when the level of CO_2 reaches 30. The assisting fan of the exhaust tower, adjacent to the solar stack, provides 0.15 m^3/s.

2.3 Control system

The HVAC system is managed by an electronic device through the survey of sensors monitoring the hygrothermic characteristics of the internal environment and according to input variables as follows (see Figure 4):

- temperatures: T_1 inside the cavity of the façade, T_2 external, T_3 internal, T_w for water tank, T_r for roof cavity;
- finned pipe (EV);
- air quality sensor (SQA);
- louvers: SA, SB, SC, SD.

The four louvers are opened in steps following different environmental conditions.
There are five different routines in the system software: cold period natural heating, cold period mechanical ventilation, warm period natural ventilation, warm period night ventilation, hot period ventilation.
The first two are active if the heating system is on. The latter three are activated when the heating system is off. The heating system is activated from the beginning of October to the end of April, which is equivalent to 80% of the opening time of the school.
Mechanical ventilation has the priority over everything else when air quality level is unacceptable and is active anyway if all the louvers are turned off. If the temperature is too high, the air in the cavity is extracted over the roof. Some common situations are shown in Table 3.

1 Cold period natural ventilation (heating system is active)	
$T_2 > 5°C$, $T_1 > 26°C$, $T_3 > 22°C$: *if $T_3 > 30°C$, loop until $T_1 > 26°C$ and $T_3 > 21°$ if not, all louvers off and light mechanical ventilation is on*	SA off SB off SC on SD off
2 Cold period mechanical ventilation (heating system is active)	
$T_2 > 20°C$, SQA < 10: *loop until SQA < 5, if not all louvers off* EV on	SA on SB off SC off SD on
3 Warm and hot period natural ventilation (heating system is not active)	
$T_2 < T_3$, $T_1 < 26°C$, $T_3 \leq 24°C$: *loop until $T_1 > 24°C$ if not, all louvers on every 10 min*	SA off SB on SC off SD on
4 Warm period night ventilation (18pm, 6 am) (heating system is not active)	
T_3 at 18 pm >18°C; $T_2 < T_3$, $T_2 > 12°C$, $T_3 > 20°C$: *loop until $T_1 > 24°C$*	SA on SB on SC on SD on

Table 3. Temperatures and louvers situations

2.4 Stack effect

When the flow is caused by thermal forces the ventilation rate in the vertical duct, from Bernoulli’s equation, is:

$$Q = K\Omega[2gH(T_3 - T_2)/T_2]^{0,5}$$

Where:
K is the coefficient of resistance = 0,40+0,0045 (T_i-T_e),

Ω is the air duct section,
H is the vertical distance between the two openings.
This equation can be applied without any heat gain from the surfaces of the duct.
The case of the generic duct can be extended to the space of our classroom with two openings, one at the bottom and one corresponding to the bottom opening of the chimney; an additional thermal power is given by the radiant panels in the classroom.
The equations to be considered are:

$\rho_2 A_a v_a = \rho_{3d} A_d v_d$ Mass conservation

$Q_s = c_p \rho_2 A_a v_a \Delta T = c_p \rho_{3d} A_d v_d$ Energy conservation

ΔT_2 is the difference between internal and external temperature at the top opening.
Internal pressure is given by (Andersen 1995):

$$p_i = p_{in} - g\rho_{in} y + 0{,}5 g\rho_{in} a y^2/T$$

where a = internal temperature gradient
p_{in} [Pa] and ρ_{in} [kg/m^3] are the pressure and the density at the level of the neutral axis.
Ventilation is also improved with solar chimneys. The contribution of the incident solar radiation q is expressed in terms of "specific stack effect"

$$U = \left(\frac{\alpha B}{\psi}\right)^{\frac{1}{3}} \text{ where } B = \frac{g\beta q}{\rho C} \; [\mathrm{m^4/s^3}]$$

B is the coefficient of air expansion, C is the specific heat
A is the factor of geometric configuration and is 0,5 with uniform thermal distribution

$$\psi = \frac{A}{H}\left\{\lambda_{fric}\frac{H}{D} + \frac{1}{2}\left[(1+k_{in})\left(\frac{A}{A_{in}}\right)^2 + \left(\frac{A}{A_{out}}\right)^2\right]\right\}$$

3. SIMULATION

The simulated rooms are two single classrooms at the ground level, surrounding square toilets. The whole building (both classrooms) is 21 m wide (x), 6 m deep (y) and 3 m high (z) and occurs three times in the school compound.

Four stacks 3.6 m high and with a diameter of 0.70 m are situated behind the toilets.

3.1 CFD Modeling

The 3D model, a fluid volume of 305,52 m³, has been divided with CFX-Mesh into 32447 tetrahedra with 10912 nodes.

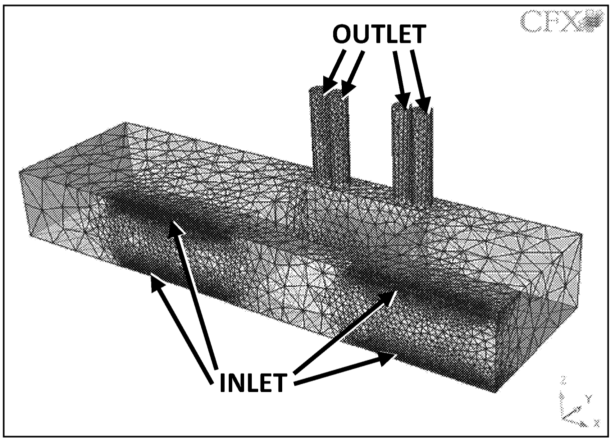

Figure 5. CFX-Mesh

Simulation has been carried out to demonstrate the stack effect efficiency or to recognize its weakness. The theoretical model is based on the solution of the governing equations of the fluid flows combined with a turbulence model. This way, detailed flow rate and heat transfer can be predicted. The turbulence model used is large eddy simulation (LES) within the software Ansys CFX 10.0.

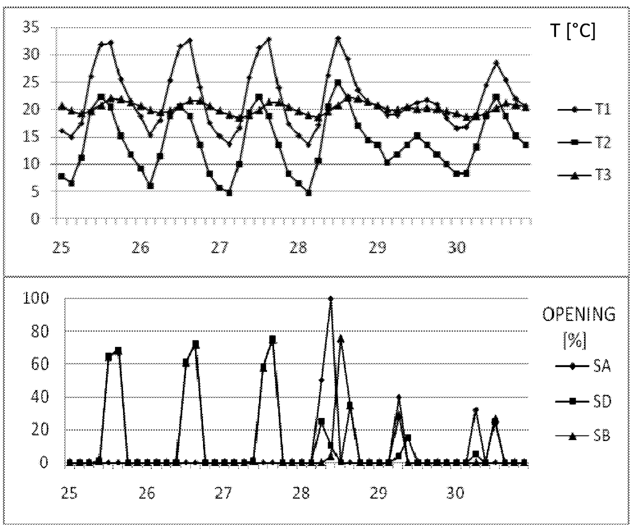

Figure 6. Temperature values and louvers openings

LES model is the most useful one to predict istantaneous flows, and in this case was the only one providing mathematical convergence.
Even if the best condition for stack effect efficiency is summer, this case is not very interesting to consider cause the school is closed in hottest months such as June, July and August. The relevant case for design and examination is the intermediate season when heating is off and internal and external temperature have a little gradient (2 or 3 °C).
For Bologna zone (Latitude: 44° 29' 44" North) solar radiation is assumed as in Table 2 (UNI 10349:1994).
The case simulated (see case 4 in table 3) refers to the month of April (see monitored temperatures from 25th to 30th in figure 6).

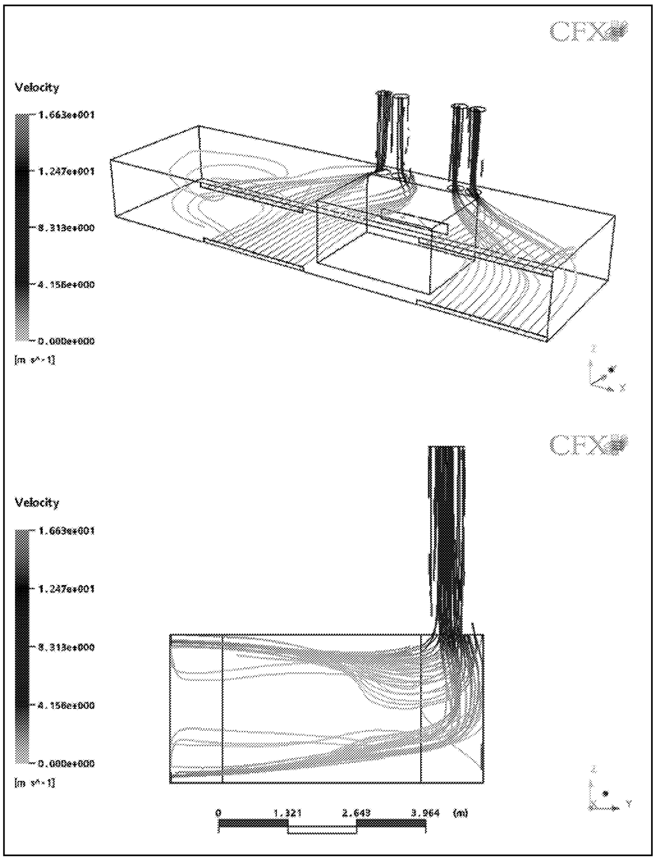

Figure 7. Perspective and side view

Monitored data show louvers opened at 50-70% of their capacity for 2-3 hours near the peak external temperature for 70% of days.
Input data are: temperature, pressure, flow direction, solar radiation. Inlet is in south side, and the protection of sunscreens has been taken into account with a correction factor.
External stack surface, made in aluminum, has a very low emissivity value and it is subject to a big temperature increase if exposed to solar radiation. Thanks to this temperature gradient caused by the sun, natural ventilation is ensured even in the described conditions.
Temperature gradient, indeed, has an effect to air density, so that the necessary low pressure to sucking up is reached.

3.2 CFD Results

The output of CFX simulation is shown in figures 7 (perspective and side view).
Flow lines, entering from the two series of louvers, upper and topper, get around the toilets and reach the stacks increasing their velocity from 0, initial condition, to 7 m/s. This very high value, similar to forced ventilation one, is the demonstration that the air, very slow into the rooms, arises quickly through the stacks.

4. CONCLUSIONS

All considered, conditions represented in CFX simulation, in which natural ventilation is actuated, are quite rare in relation to the overall opening period of the building (only for 2-3 hours/day). The activation due to CO_2 condition is prevalent in respect to natural behavior and reducing this dependence with a better sensor calibration would increase natural stack effect with energy savings. In accordance to the simulation results, data monitored in March-May 2008 have proved that the system, in almost theoretical operating condition, is – even partially – naturally working.

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