USE OF THE STAIRWELL AS A COMPONENT OF NATURAL VENTILATION SYSTEMS IN RESIDENTIAL BUILDINGS. COMPARISON OF TECHNOLOGIES FOR THE EXTERNAL ENVELOPE.

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ABSTRACT

The design and realisation of natural ventilation systems is an important research topic into the ability of buildings to respond to climatic conditions, using parts of the buildings themselves as indoor microclimate control systems. This research aims to evaluate how the stairwell can be an essential element of natural ventilation in low-rise buildings. In this study, the main innovation is the different architectural and functional conception of traditional building components such as the stairwell.
The stairwell is used as a chimney in order to increase the air exchange rate in cold and hot seasons. While previous works of the author were focused on the ventilation in winter, when the heating of dwellings enhances the stack effect in the stairwell, in this paper the summer behaviour of similar systems has been be investigated. The hypothesised driving forces causing air movement are the stack effect and the “solar chimney effect”.
In this paper the application of the described systems is analysed on common building types, such as blocks of "in-line" housing. These consist of three to five storeys with a single stairwell and two apartments on each floor. The natural ventilation system studied is characterized by easy implementation in energy retrofitting of buildings as well as inexpensive installation and management. In order to increase the “solar chimney” behaviour, two different technical envelope solutions have been evaluated, namely painting external surfaces black and external insulation. The effects produced by the implementation of different façade systems (equipped with PV systems, transparent insulating materials, air collectors and advanced envelope systems) will be compared in future works.
Finite elements and Computational Fluid Dynamics codes were used in order to design and verify the intervention efficiency and the behaviour of the system as a whole . The first results of CFD simulations here presented highlight that the fluid patterns can play a fundamental role. The complex geometry and the dynamic thermal boundary conditions of a typical stairwell substantially modify the hypothesised “solar chimney behaviour” of the system at night.

KEYWORDS
Natural Ventilation, Stairwell, Residential Buildings, CFD

INTRODUCTION

This research aims to evaluate how stairwell can be an essential element of natural ventilation in low-rise buildings and follows on from previous research by the authors (Catalano et al., 2004).
This study focuses on building types that are very common, such as blocks of in-line housing. While previous works have evaluated the behavior of the stairwell as an extractor chimney during winter, in this paper the mechanism of the optimized winter system is evaluated during summer conditions.

1. THE NATURAL VENTILATION SYSTEM: THE MODEL AND ITS BOUNDARY CONDITIONS.

The analyzed system is a typical stairwell of an in-line multi-family building of five storeys, with two dwellings per floor. The following figures show the typical plan and sections of the adopted model. The same system has been analysed in typical winter boundary conditions. Furthermore, the behaviour of a stairwell with a sloped roof (see figure 1) has been verified.

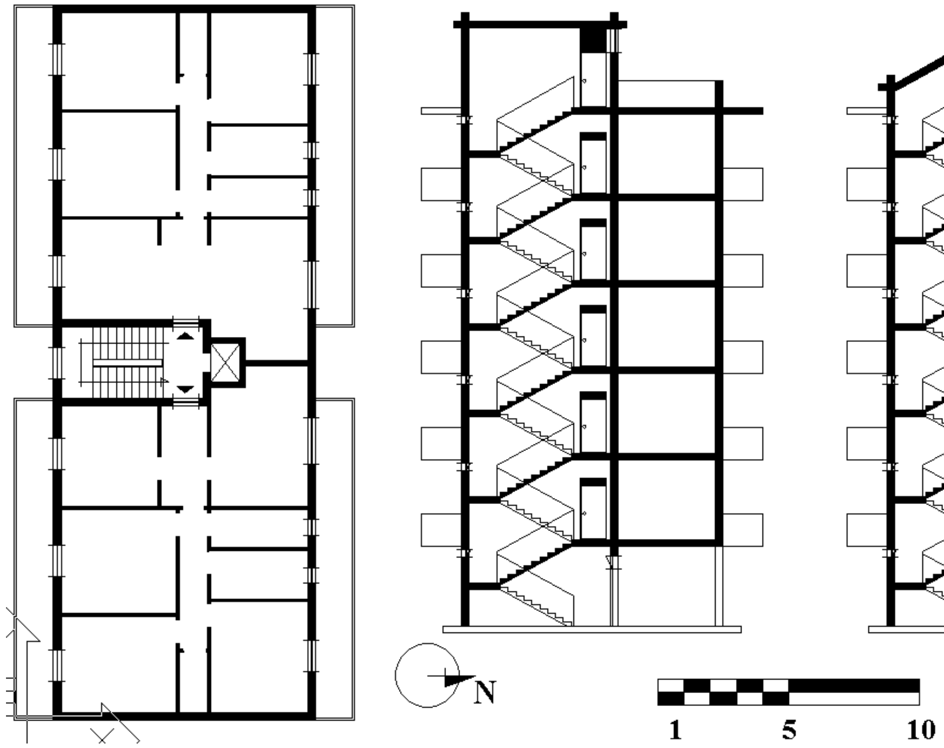


Figure 1: the adopted model: typical plan and section

The main components of the ventilation system for each apartment are:

- wind-sheltered inlets located near windows or heating devices (for example, a grille mounted into an external wall or windowsill, equipped with adjustable deflectors);
- air-transfer device (for example, grilles mounted into the internal doors);
- operable louvers mounted at the top of the entrance unit;
- semi-automatic control system (each occupant can manually adjust the air-inlets of some or all the rooms to suit personal requirements).

The natural ventilation system has been designed in order to extract the exhausted air from each apartment and each unit is sealed off from the others. These are important characteristics of the ventilation system in order to avoid a short-circuit and guarantee adequate indoor air quality (IAQ) in each unit.

Citing the conclusions of the previous works (Catalano et al., 2004), during winter, the studied stairwell is able to improve indoor ventilation, thanks to the pressure gradient between the stairwell and apartments, given by an internal temperature gradient.

The general aim of the developing research is to evaluate the summer behavior of this system with the following hypothesis:

- it is necessary to consider the behavior of the global system in transient state, providing variable external and internal heat fluxes, and simulating the real thermal inertia of the envelope;

- in order to verify the behavior of the model during summer, the effects of total solar radiation incident on the stairwell surfaces (the south wall, the walls at the top and the roof) have been taken into account (no shading of the envelope);
- no flat is equipped with an HVAC system: the only way to cool the apartments is natural ventilation. In this way, by eliminating the effect of internal heat loads, the internal air temperature is the same as the external one.

The hypothesised driving forces causing air movement are:

- the stack effect;
- the "solar chimney effect": the south wall warms air in the stairwell, causing it to rise toward the roof; this warmed air is extracted at the top of the stairwell and, consequently, fresh air is supplied to each dwelling.

The wind effects were ignored (the above mentioned mechanisms may be more affordable and continuous than wind-induced ventilation, especially in urban areas).

With the aim of maximizing the solar contribution, a statistical mean day in the month of July was chosen as the simulation date (in which, both the outdoor temperature and total vertical irradiance reach maximum values).
The city chosen as the location for simulations is Bari (41° 7' N – 16° 46' E), in the south of Italy. For this location, implementing solar radiation models (Muneer, 2004), mean values of hourly global solar radiation were estimated. Furthermore the external hourly mean temperatures were obtained from CNR (1982).

As previously mentioned, the effect of the thermal inertia of the traditional stairwell envelope was taken into account, trying also to suggest retrofitting intervention able to improve the "solar chimney effect", by means of a suitable shifting of the thermal wave and to enable the energetic upgrading of the envelope in general.

For this reason, during a first simulation step the heat transmission of traditional and retrofitted walls were evaluated (also reported in table 1) while in the second step a CFD simulation of the global stairwell model was carried out.

TABLE 1: thermo-physical characteristics of external traditional walls (1-4) and retrofitting intervention (5-7)

Id number	Type name	layers	width [cm]	λ [W/m °C]	c [MJ/m³°C]
1-2	Single layer perforated brick wall (20-30 cm)	External plaster	2	0.9	1.62
		Perforated brick	20-30	0.35	0.47
		Internal plaster	1	0.8	1.62
3	Concrete wall (30 cm)	Concrete	30	2.7	1.83
4	Single layer tufa wall	External plaster	2	0.9	1.62
		Tufa	30	0.65	1.65
		Internal plaster	1	0.8	1.62
5	Externally insulated perforated brick wall	External plaster	2	0.9	1.62
		Insulation (polystyrene)	4	0.024	0.059
		Perforated brick	30	0.35	0.47
		Internal Plaster	1	0.8	1.62
6	Externally insulated concrete wall	External plaster	2	0.9	1.62
		Insulation (polystirene)	4	0.024	0.059
		concrete	30	2.7	1.83
7	Externally insulated tufa wall	External plaster	2	0.9	1.62
		Insulation (polystyrene)	4	0.024	0.059
		Tufa	30	0.65	1.65
		Internal plaster	1	0.8	1.62

2. ANALYSIS OF HEAT TRANSFER THROUGH EXTERNAL WALLS

In order to compare different envelope solutions we simulated the thermal behavior of traditional (local) walls and retrofitted ones using the following methodology.
For the temperature affecting the exterior surfaces, a theoretical temperature was used, considering the effect of the outdoor air temperature and the absorbed solar energy and indicating periodical change. In this way the so-called "sol-air temperature" was calculated using the following formulation (Threlkeld, 1998):

$$T_{sa} = T_{out} + \frac{\alpha}{h_{out}} R_{tv} - \frac{\varepsilon \, \Delta R}{h_{out}}, \qquad \text{Eqn. 1}$$

where T_{sa} is the sol-air temperature, T_{out} is the outdoor air temperature, α is the absorptivity of the external surface, h_{out} is the outdoor convective heat transfer coefficient, R_{tv} is the total radiation for vertical surfaces. The last term in Eqn.1, the correction factor, is assumed to be equal to 0 for vertical surfaces, following the ASHRAE recommendations.

Regarding the absorptivity of external surfaces, the solutions of white-painted (α=0.25) and black-painted external surfaces (α=0.90) were evaluated and, consequently, hourly values of sol-air temperature were calculated.

The internal heat flows (Q_{in} and Q_{out}) and surface temperatures were calculated with the aid of Heat 2.0 software, developed by the Department of Building Physics of the University of Lund (Sweden). The walls simulated, often used for the stairwell envelope in the south of Italy, are those in table 1. The results of these simulations are in the following table 2 and figure 2.

The simulations conducted show how concrete walls, both traditional and externally insulated, are able to maximize internal heat exchanges thanks to their considerable heat storage masses, also providing a good delay of the thermal wave.
The highest shift is, however, given by tufa walls, that also provide good heat exchange.
It is also necessary to consider that the differences between the behavior of analyzed systems will decrease in the global CFD model, which also takes into account internal surfaces and masses.

TABLE 2: results of the simulations: internal heat flows (Q_{out}= heat transmitted to the stairwell, Q_{in}=heat transmitted to the wall) and hours of flux inversions.

Id number	Type name	flux inversion	Q_{out} [Wh/m^2]	Q_{in} [Wh/m^2]	flux inversion	Q_{out} [Wh/m^2]	Q_{in} [Wh/m^2]
		painted white (α=0.25)			painted black (α=0.90)		
1	Single layer perforated brick wall (20 cm)	5:30 A.M. 1:30 P.M.	116	65	5:30 A.M. 11:30 A.M.	250	47
2	Single layer perforated brick wall (30 cm)	5:30 A.M. 3:30 P.M.	110	73	6:30 A.M. 1:30 P.M.	201	53
3	Concrete wall (30 cm)	6:30 A.M. 3:30 P.M.	243	105	7:30 A.M. 11:30 A.M.	591	37
4	Single layer tufa wall	7:30 P.M. 5:30 P.M.	159	97	7:30 P.M. 3:30 P.M.	295	46
5	Externally insulated perforated brick wall	6:30 A.M. 5:30 P.M.	86	72	6:30 A.M. 4:30 P.M.	115	57
6	Externally insulated Concrete wall	7:30 A.M. 7:30 P.M.	158	149	7:30 A.M. 6:30 P.M.	190	120
7	Externally insulated tufa wall	6:30 P.M. 7:30 P.M.	103	122	6:30 P.M. 6:30 P.M.	130	98

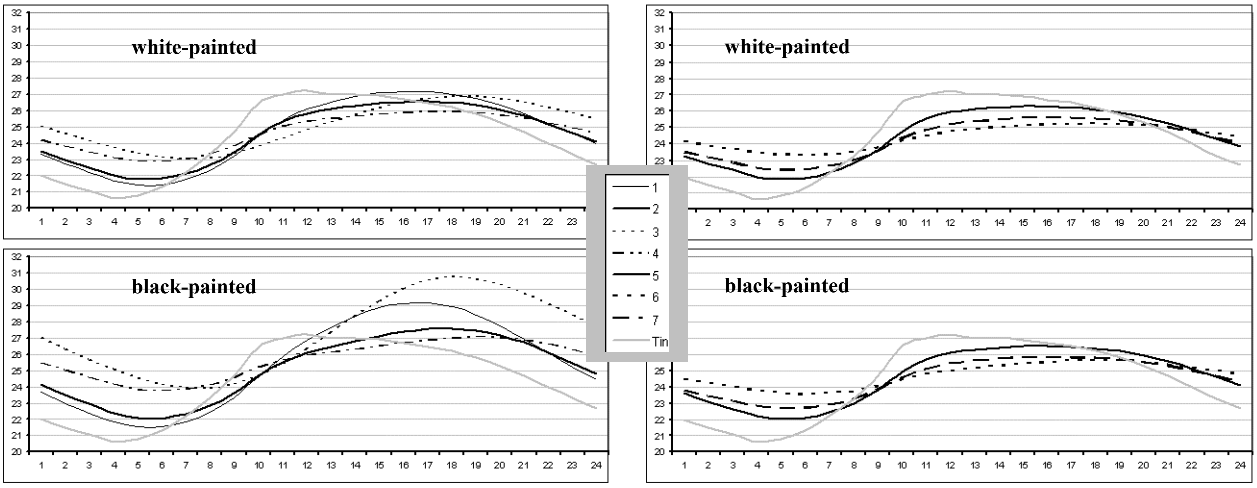


Figure 2: internal surface temperature for traditional (1-4) and retrofitted (5-7) walls

3. THE NUMERICAL CFD SIMULATIONS: RESULTS AND DISCUSSION

The model used in CFD simulations was simplified in order to optimise the computational time:

- the pressure losses in the apartment path were collapsed into a single resistance (therefore, only the stairwell was modelled);
- the stairwell geometry was simplified and reduced to the essential components (flights of stairs, landings, steps);
- the openings were modelled as simple resistance or as simple sloping planes.

The locations, the sizes and the pressure losses of openings were optimised in order to extract the air and to balance the airflow rate from each dwelling. The balanced system described in Catalano et al. (2004) (optimised for winter regime) has been used for the summer period.
The CFD numerical simulations were run in order to evaluate:

- the behaviour of the stairwell as an extraction device in summer (chimney and solar chimney);
- the effects of different envelope solutions (traditional and refurbished ones);
- the effects of different roof solutions at the top of the stairwell (flat and sloped roof);
- the behaviour of the system for different ventilation strategies (24 hours or night ventilation).

The CFD simulations highlight that the system is characterised by two different mechanisms (stack effect behaviour in day-time and solar chimney behaviour at night) :

- in the day-time, the air exhausted from dwellings rises in the stairwell, flowing along two main patterns: the first flow path is helicoidal in shape (just below the flights of stairs and landings), the second is a vertical path along the core of the stairwell; the results shown in figure 3a highlight that the air is extracted from all the dwellings
- at night, at lower levels (first to fourth floor), the air near the external wall is heated up and then rises along the walls, the landings and the flight of stairs. This warmed air mixes with the colder air extracted from dwellings, flows downward along the flight of stairs and returns back to the external wall (figures 3b and 4).

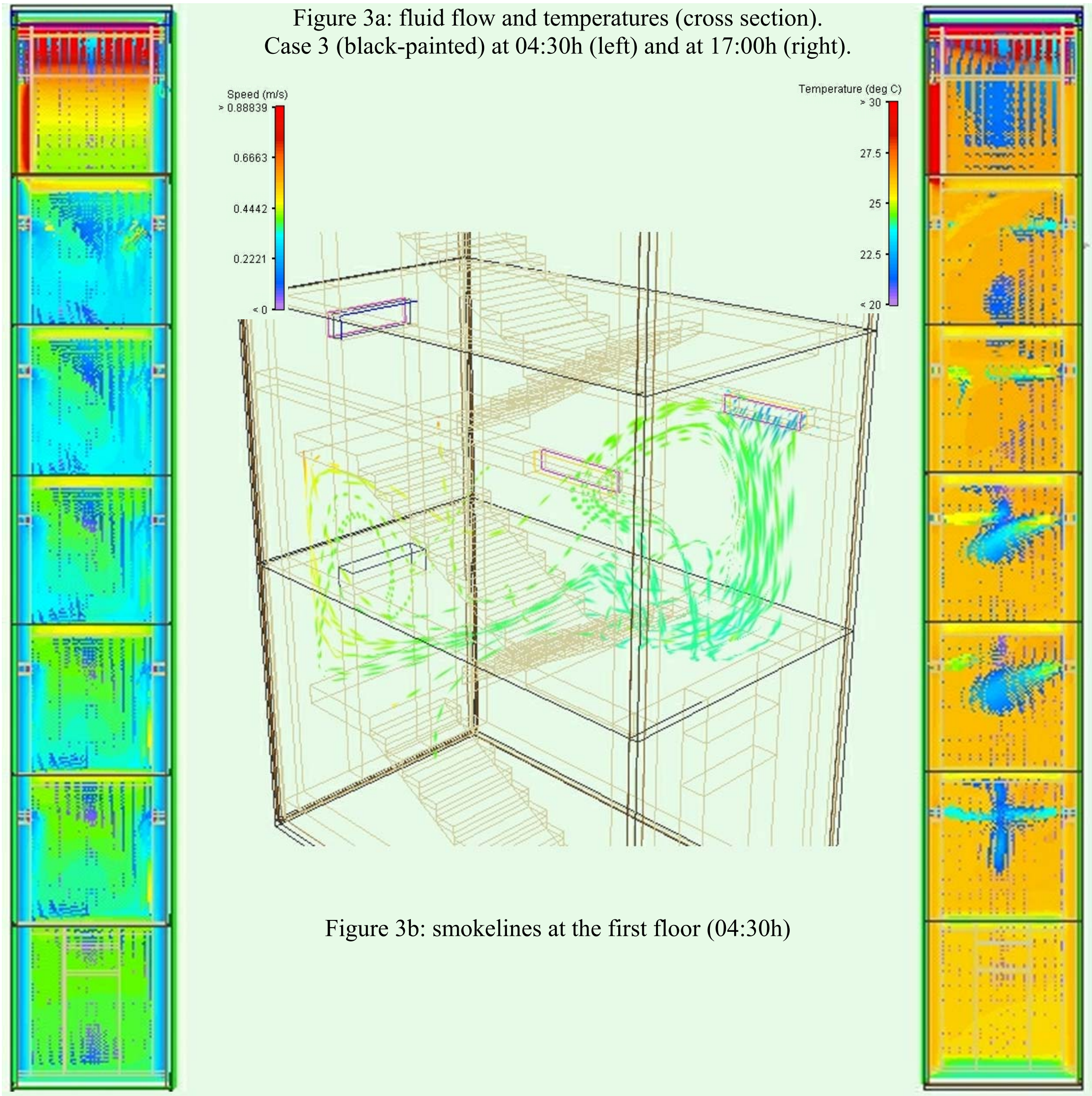


Figure 3a: fluid flow and temperatures (cross section).
Case 3 (black-painted) at 04:30h (left) and at 17:00h (right).

Figure 3b: smokelines at the first floor (04:30h)

In detail, the CFD simulations highlight that (figures 4 and 5):

- thermal inversion (the air enters the dwellings at night) is observed when the heat stored in the external walls is low or the delay of heat released to the stairwell is low (case 1, perforated brick wall, 20 cm);
- the airflow rates are high in day-time and low at night;
- the airflow rates increase with the heat accumulated in the external walls;
- the shift in maximum and minimum airflow rates is related to the delay of the thermal wave but not as expected;
- the effects of a sloped roof on the main behaviour of the system are poor (except for the fifth and the fourth floor);
- the ventilation strategies (24 hour or night ventilation) do not affect the main behaviour of the system;
- the refurbished external walls (painted black or covered by an external thermal insulation layer) allow higher airflow rates both in day-time and at night, but the airflow rates seem to be inadequate for night ventilation strategies.

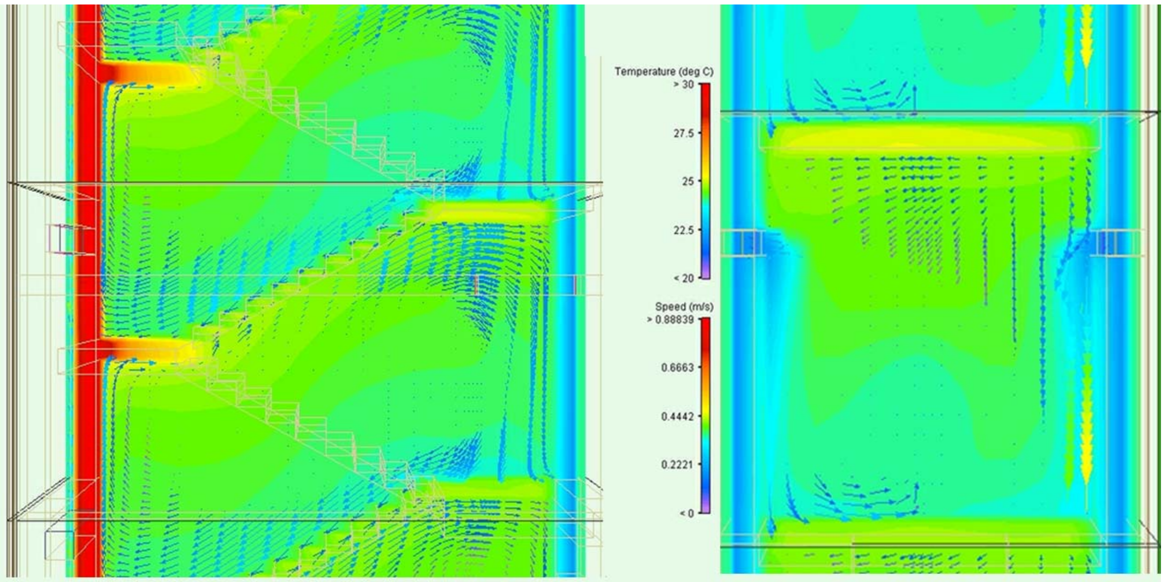
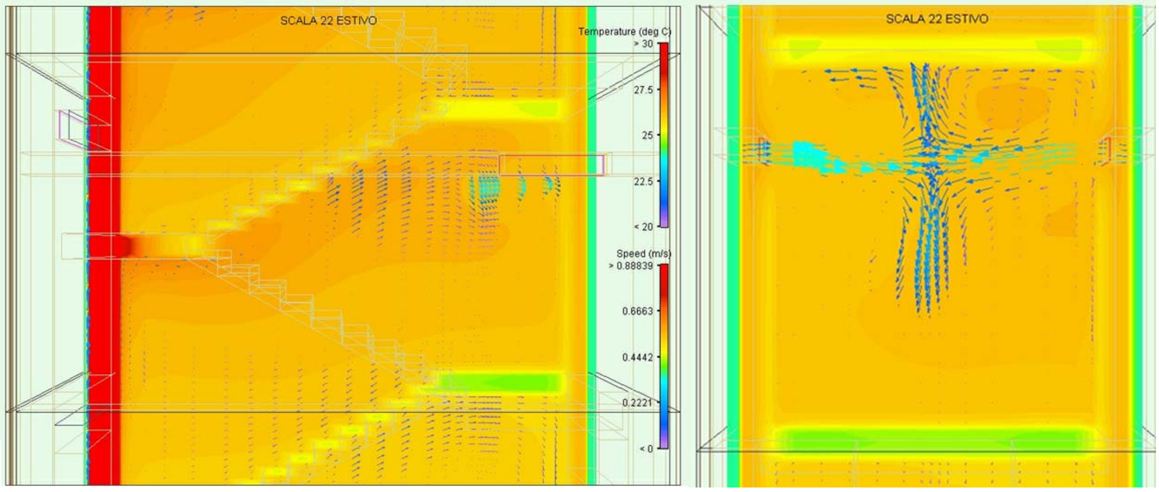


Figure 4:details of fluid flow and temperatures at the first floor (longitudinal and cross section). Case 3 (black-painted) at 04:30h (above) and at 17:00h (below).



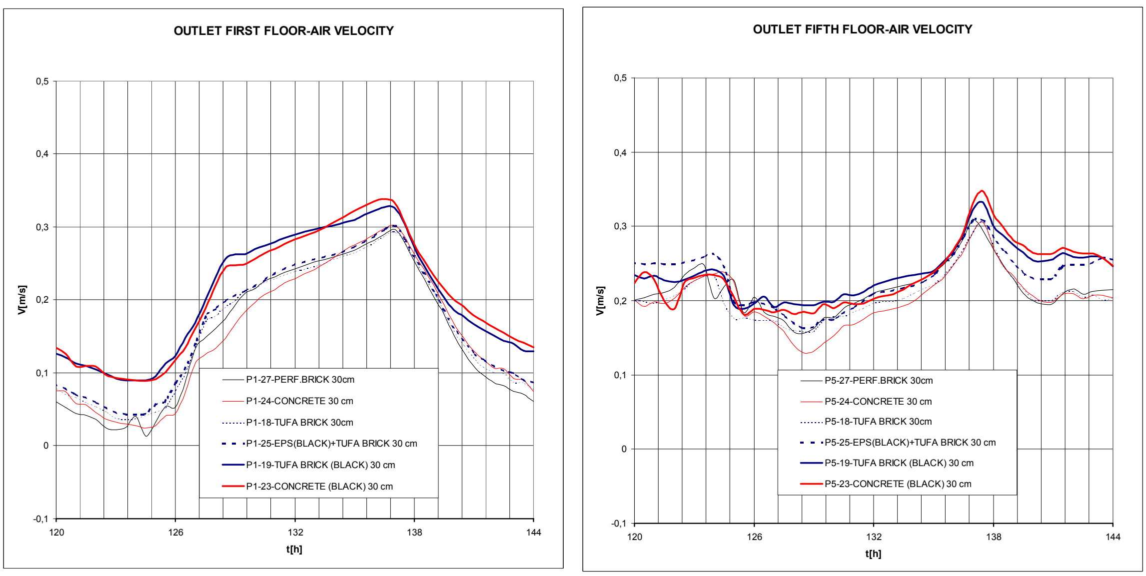


Figure 5: air velocity near the air-transfer device at the top of the entrance unit (grilles at the first and fifth floors).

In conclusion, the CFD simulations show that fluid patterns can have a fundamental role: the complex geometry and the dynamic thermal boundary conditions of a typical stairwell substantially modify the hypothesised behaviour of the system at night. It is worth noting that the temperature of air extracted from dwellings is generally higher than that hypothesised and this temperature is related to the internal thermal loads and the ventilation rates.
Further simulations will be run to test different systems that can enhance the "solar chimney behaviour" at night. The first idea is to break the thermal loop shown in figure 3b by means of openings located on the half landing or by adding conveyers at the bottom of the half landings that drive the warmed air toward the central void of the stairwell. In addition, methods of refining air temperatures of dwellings will be evaluated.

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CONTRIBUTORS

F. Iannone planned and supervised the study, executed the CFD simulations and analysed the data (paragraphes 1 and 3). F. Fiorito codesigned the study and executed the analysis of heat transfer through external walls (paragraphes 1 and 2).