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Analysis of Ancient Natural Ventilation Systems inside the Pitti Palace in Florence

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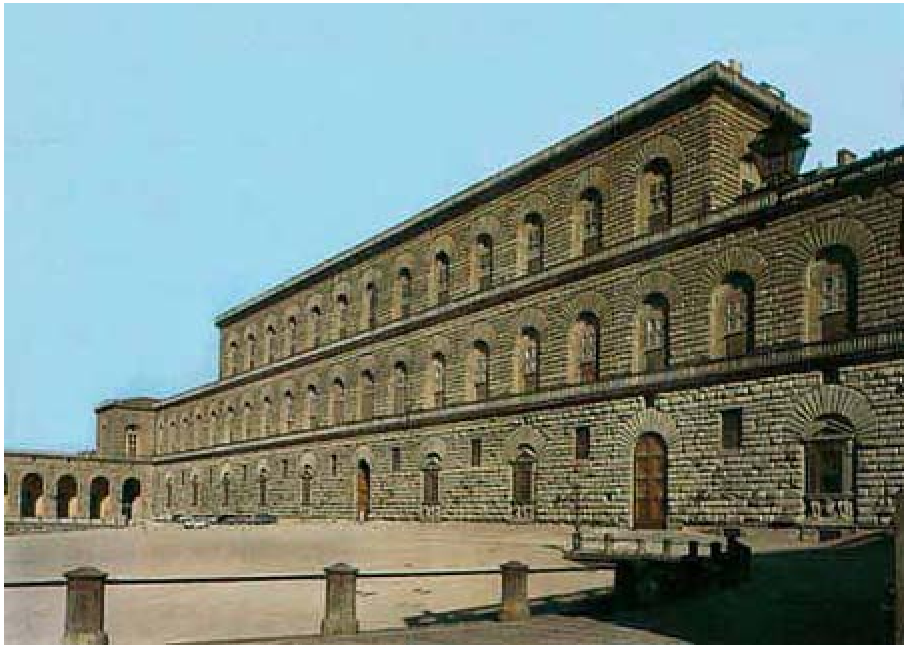
Some architectural structures, inside historic buildings,
are often interpreted as cooling systems.

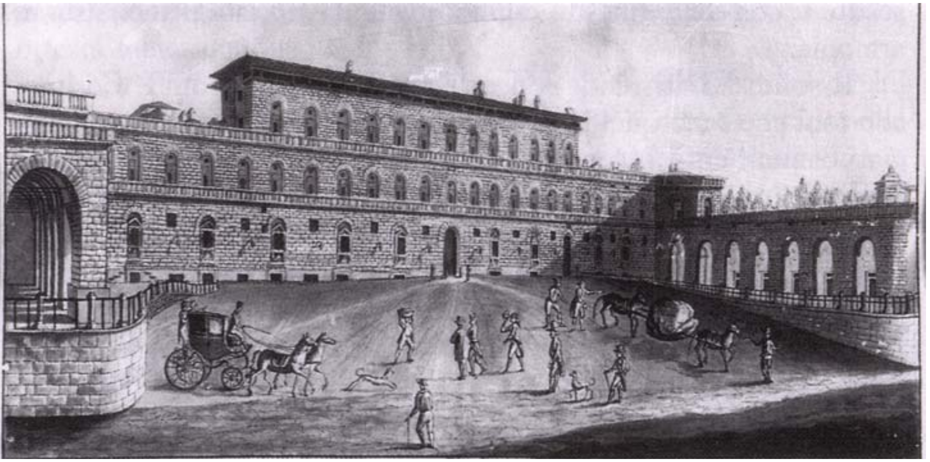
The problem is the knowledge
of their real working in the past and at present.

This work presents and discusses
the first phase results, of an interdisciplinary,
wide ranging project, concerning the
study and prediction
of the efficiency and energy performances
of natural ventilation systems existing inside historic buildings

The building studied

The *Pitti Palace* in Florence is one of the most important example of natural ventilation systems in the Italian Cultural Heritage





The ambient studied

All the historic maps and data collected by a direct survey using a scanner-laser 3D, were used to set up the physical scaled model and the 3D architectural drawing model of the palace.

The rooms belonging to Parigi's project, located in the left wing, at present occupied by the Silver Museum, were analysed and investigated.

The floors of these rooms have white rose gratings. They are connected to the cavities dug inside the floor thickness. These elements recall the rose windows of Palladio's Villas in Costoza (Italy).

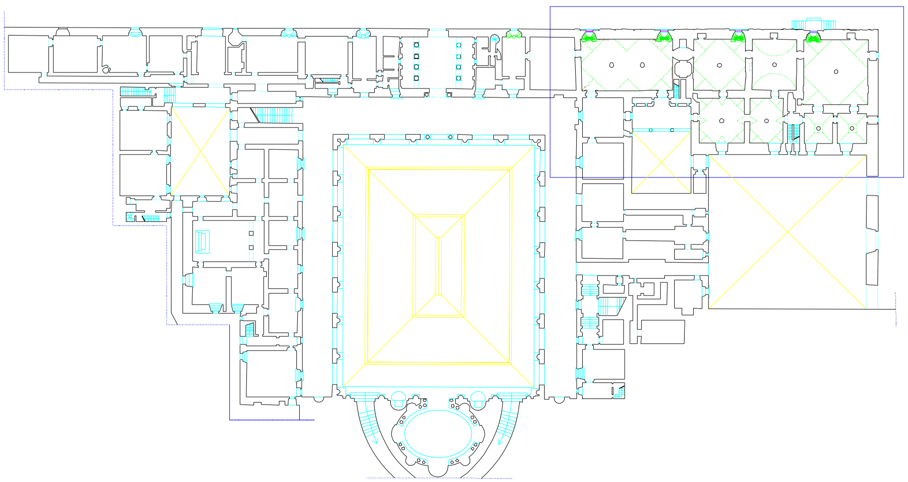


Figure 1 Pitti Palace, ground level

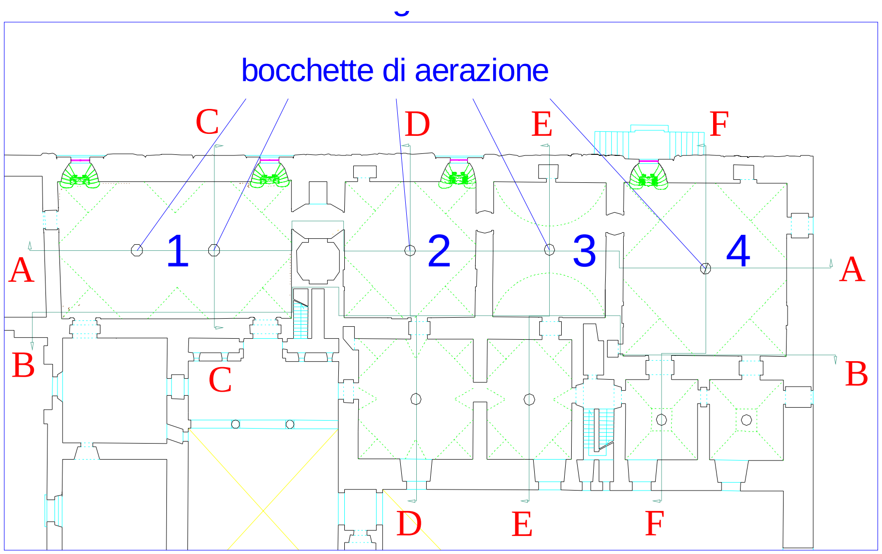


Figure 2 Pitti Palace, ground level, investigated rooms

The ambient studied

The cool air from Boboli Gardens enters the basement windows and then, due to the chimney effect, goes up from the basements to the rooms above.

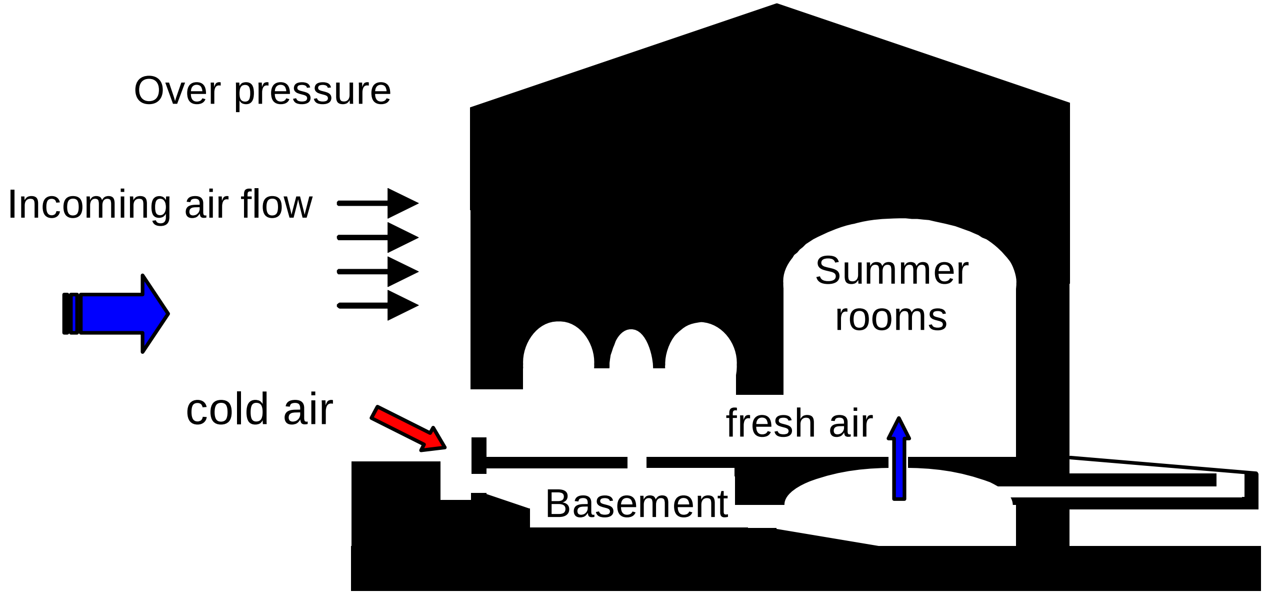


Figure 3 Pitti Palace - the air recirculation hypothesis

Modelling and Simulation

A transient simulation was performed on the system limited to the two rooms of the left part of the Pitti Palace (they were also investigated by boundary-layer wind tunnel tests).

Figure 4 shows the domain studied by the transient simulation.

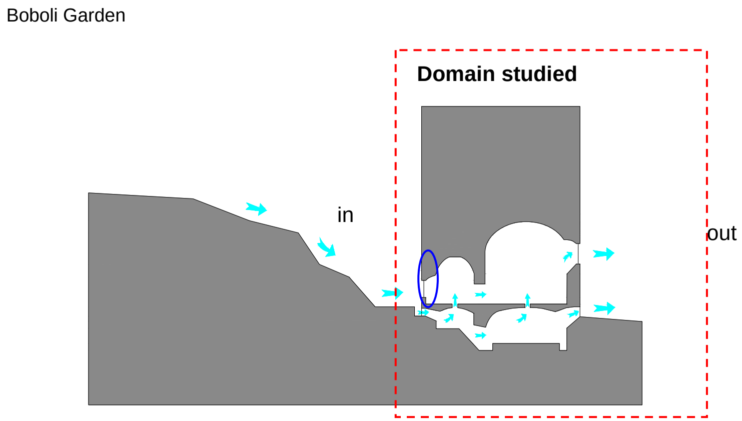


Figure 4 Pitti Palace - the domain studied

To investigate the development of the ventilation flow inside the rooms studied, a time dependent simulation based on general heat transfer and the incompressible Navier-Stokes model on non-isothermal air flow, was performed using Comsol Multiphysics software.

Modelling and Simulation

A three dimensional model of the geometry of the ambient studied was carried out disregarding the surrounding garden, *Piazza Pitti* and the adjacent rooms.

The mesh density was selected after many attempts in order to combine solution accuracy with reduction of computational time needed for convergence.

A good quality of the mesh was obtained by 945 000 degrees of freedom with 177 762 tetrahedral elements and 24 450 triangular elements.

An initial simulation concerned the stationary analysis of the 3D model to find the thermodynamic equilibrium conditions of the system.

The system solver "PARDISO" was used and the analysis was carried out for the hottest day of the Standard Year in Florence. Solar radiation was taken into account using the corrected external sun-air temperature $T_{sun\text{-}air}$ provided by the formula:

$$T_{sun-air} = T_{external} + \frac{Q_{sun} * a}{\left(h_{convective} + h_{radiative}\right)}$$

Modelling and Simulation

Conduction, convection and radiation effects to the building envelope on the flow, were modelled

All boundaries of the computational domain, (for the ventilation openings, doors connecting the adjacent rooms, outlet-pressure boundary conditions) were modelled as no-slip boundaries.

For the k-ε turbulence model in the air sub-domain, density and dynamic viscosity were considered as functions of the air temperature and the volume force, due to the buoyancy and function of air density, following the Boussinesq approximation.

The initial conditions for this transient computation were obtained by running the simulation for three days before (259 200 s) assuming, for the initial indoor climatic conditions, a uniform internal air temperature of 26°C and 50% of relative humidity

Tab.1 Climatic data of the hottest summer day

hour	External air temp. (°C)	Total horizontal solar radiation (Wm^{-2})	Relative air humidity (%)
6	17.3	79.3	0.88
7	17.8	159.9	0.87
8	19.9	244.7	0.8
9	23.0	324.9	0.69
10	27.0	391.0	0.54
11	29.5	524.5	0.47
12	31.7	694.3	0.43
13	33.6	802.6	0.40
14	35.0	835.4	0.38
15	36.0	791.1	0.36
16	36.6	680.6	0.36
17	36.0	524.7	0.38
18	34.5	348.6	0.43

Tab.2 Thermo-physical properties of the main building materials

Description	Thickness (m)	Thermal conductivity ($Wm^{-1} K^{-1}$)
Wall – local stone	1.30	2.3
Ceiling	0.31	2.2
Floor	0.46	0.5

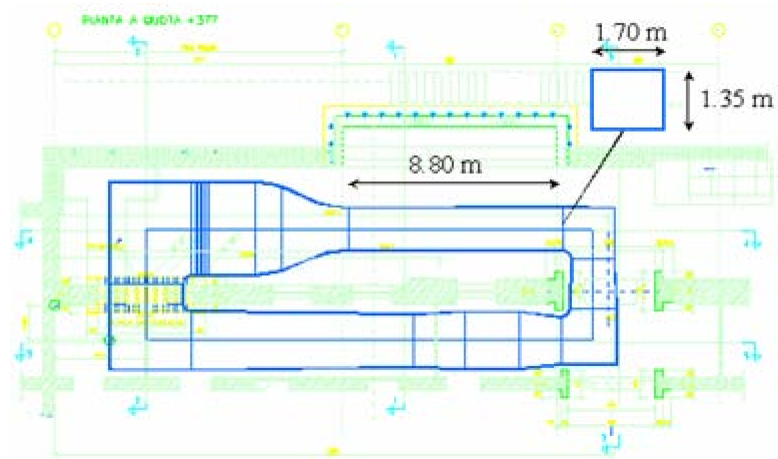
The physical scaled model and the boundary layer wind tunnel tests

The tunnel is of the open type and the target wind speed may vary in the range 0-35 m/s.

The flow speed is regulated by means of both the regulation of the pitch of the 10 blades constituting the fan and the rotating speed.

The wind tunnel has a rectangular cross-section with sides of 2.2 m by 1.6 m, slightly divergent from the inlet to the working section whose dimensions are 2.4 m by 1.6 m.

The global length of the wind tunnel (from inlet to the end of diffusers) is about 24 m: the first 11 m are used to develop the boundary layer.



Results of time dependent 3D simulation were compared with those obtained by an initial qualitative experimental measurement campaign, developed in the boundary-layer wind tunnel at CRIACIV located in Prato during a short period (two days), using the physical scaled model of the palace In particular the first experimental measurements were carried out using the CO_2 dry-ice as gas tracer, without target wind speed, and using the PIV (Particle Image Velocimetry) technique for flow visualisation and quantification.

The physical scaled model

Scaled model of Pitti Palace, front side

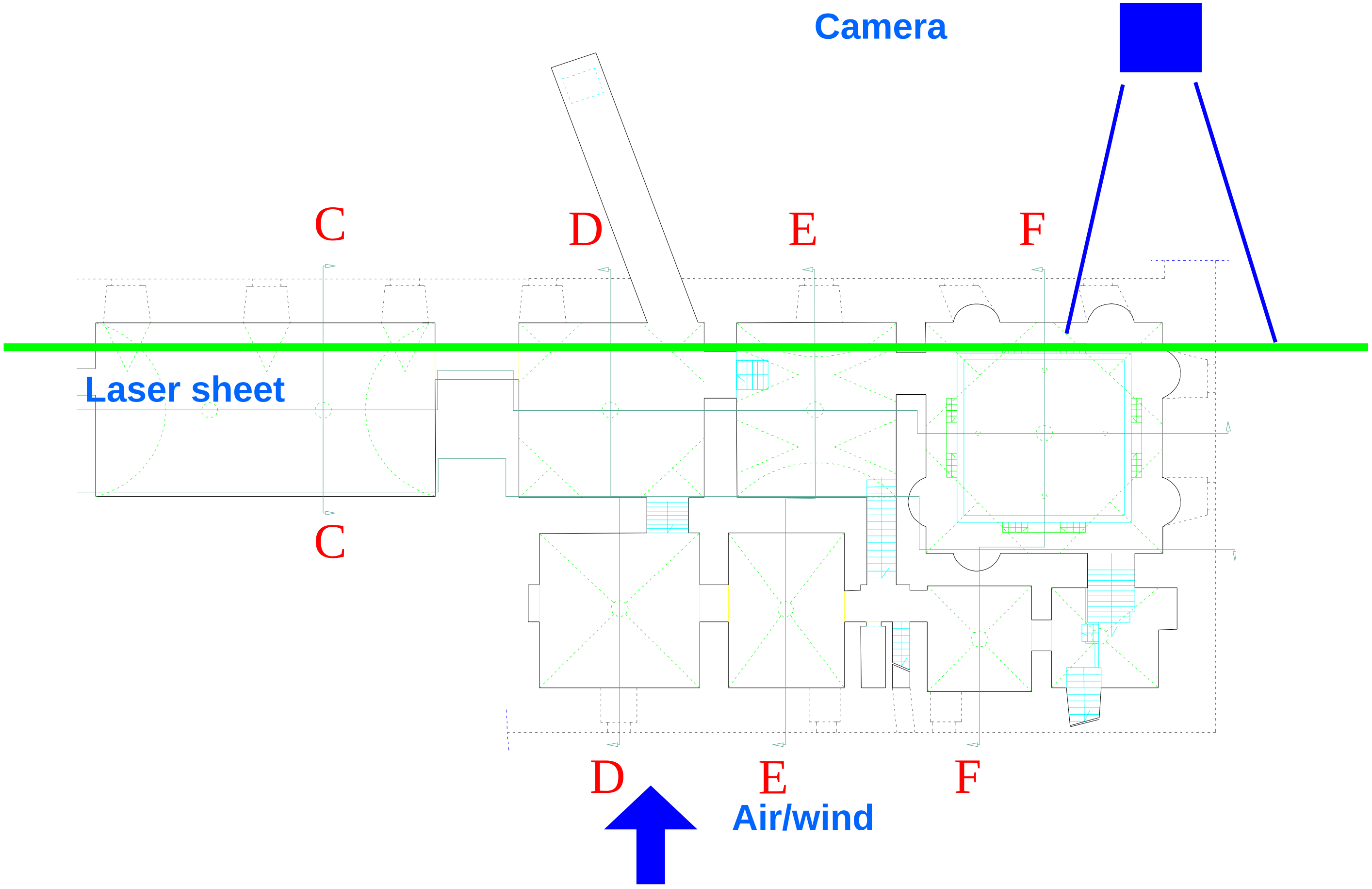
Scaled model of Pitti Palace, back yard

Scaled model of Pitti Palace, detail of the left summer apartments with transparent walls

Scaled model of Pitti Palace, back yard

The experimental tests

The camera was positioned in front of the investigated rooms, while a laser was placed above the model, generating a laser sheet enlightening the summer rooms, in a plane perpendicular to the camera (green line)



Experimental results

In this set-up (with dry ice positioned in the Boboli garden-absence of forced wind) the flux inside the summer rooms was investigated through visualization.

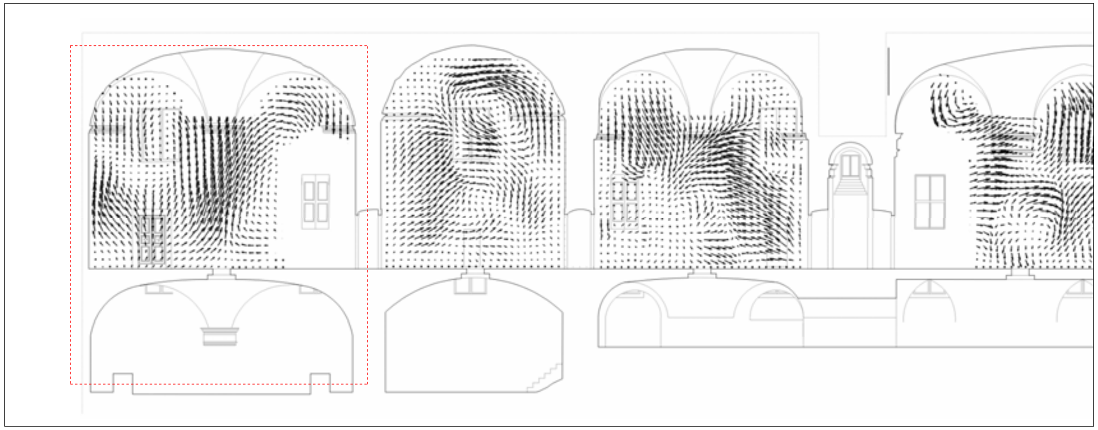
It is well visible the air movement from the "Boboli" Gardens towards the back windows due to temperature difference of the air cooled by sublimated dry ice.

This causes the movement of air generated by the adiabatic saturation process, due to green and water surfaces and ground slopes of the garden.

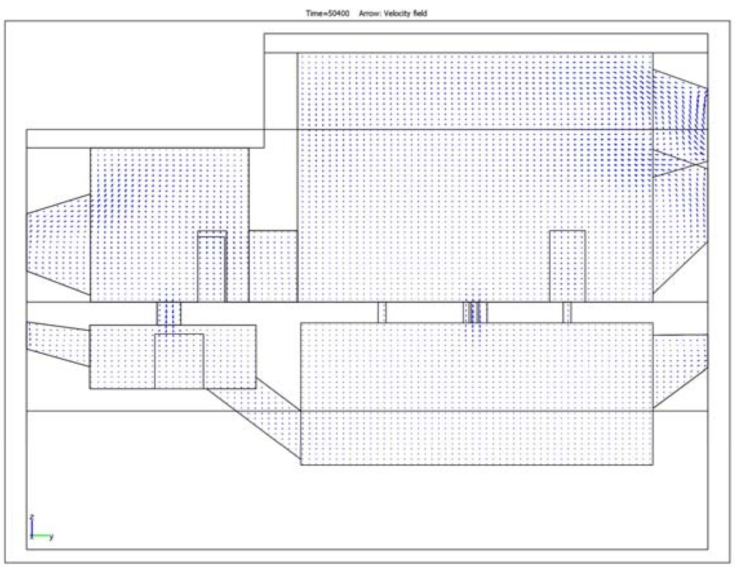
This condition causes a natural ventilation inside the building

Results comparison (experimental and simulated)

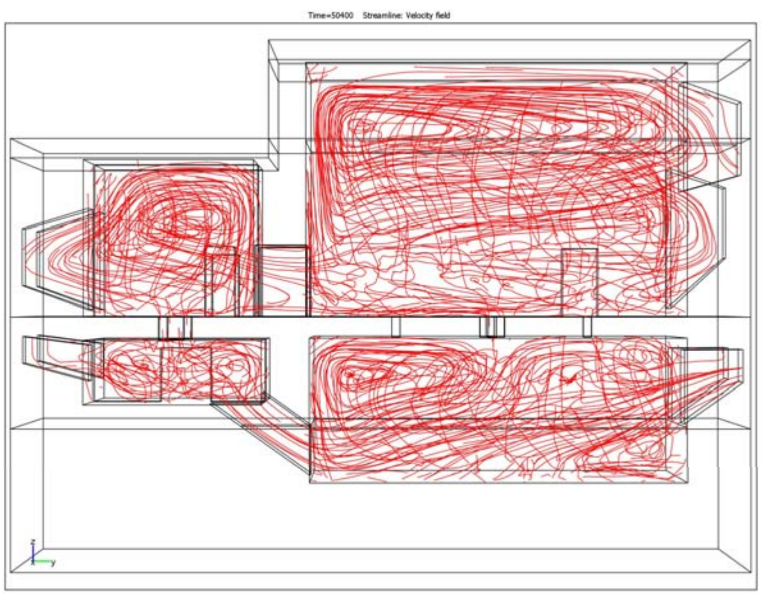
The simulation results obtained, follow the same distribution of the air velocity provided by the experimental values measured during an initial short test campaign



Vector velocity field - experimental – dotted line shows the rooms studied by simulation



Vector velocity field (Y-Z plane) simulated –July h.15



Streamline velocity field (Y-Z plane) simulated –July h.15

Results and discussion

Simulation results with slice (fig.7) and streamline (fig.8) representation of the velocity field at 15 h inside the rooms studied.

Figs 9-10 show the air distribution, at the outlet of the inside ducts and through the windows, with 2D slice representation: temperature distribution is related to mixing capacity of the velocity field that can be evaluated by comparing the heterogeneous air velocity distribution (Fig.8)

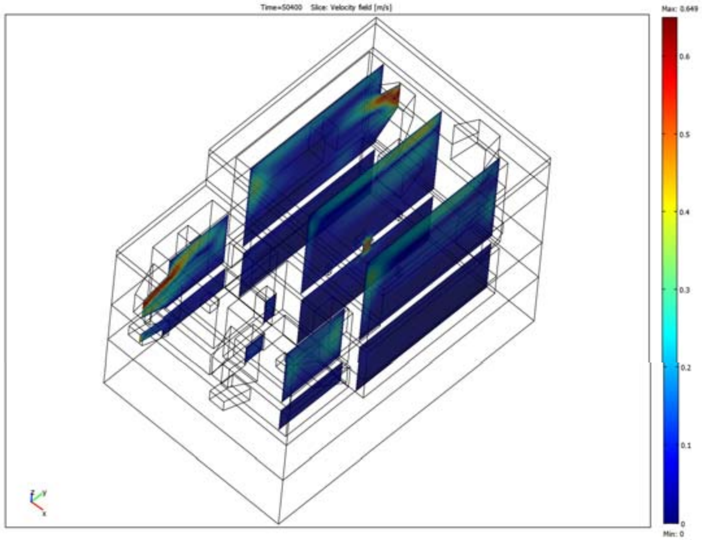
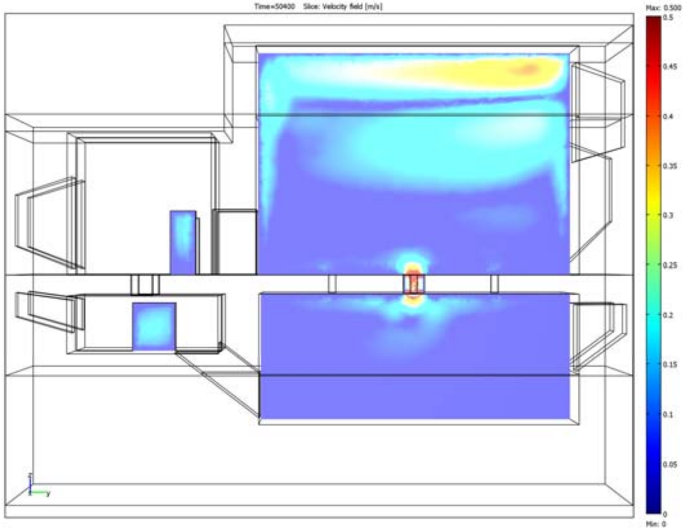


Fig. 7

Fig. 8



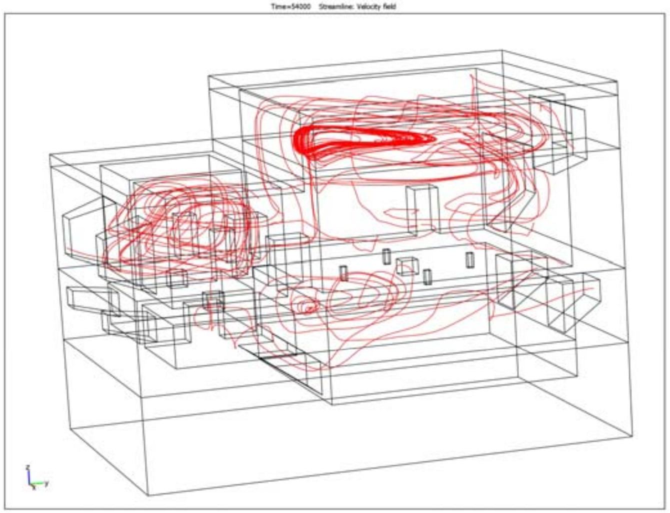
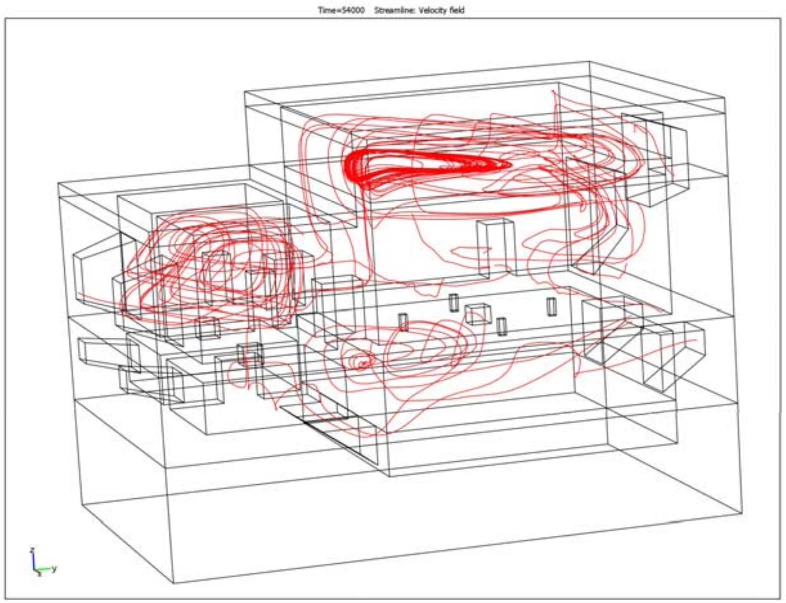


Fig. 9

Fig. 10

Results and discussion



Streamline velocity field – simulated - July h.15

The main pattern of internal air flow can be deduced: a stagnant layer was formed at the ceiling level where the air mixing can be particularly slow.
This stagnant layer is not stable moving very slowly downwards over time.

The presence of large South-West windows on the wall facing to Piazza Pitti, produces a warmer zone that locally reduces the air velocity increasing the turbulence effect and vorticity (Fig.11).

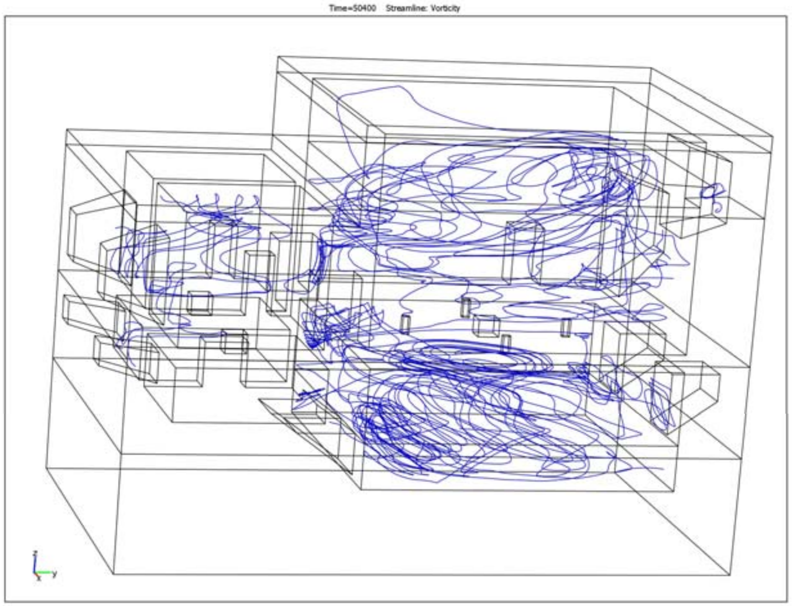
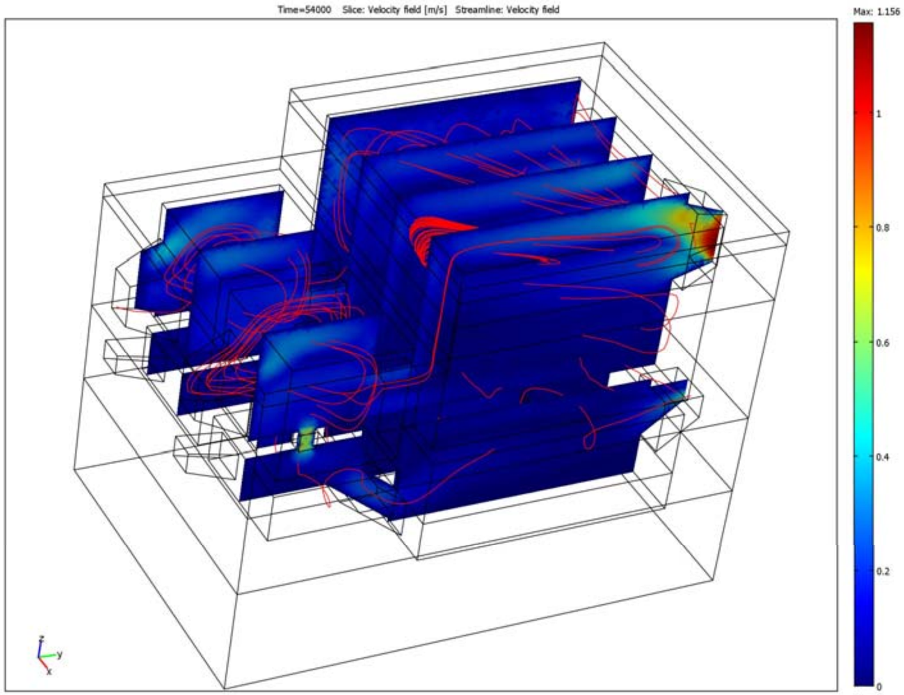


Fig. 11 Streamline vorticity field – simulated - July h.15



Results and discussion

- This study confirms the operating of an ancient natural ventilation system inside a historic building

- Computational time needed for convergence was 168 hours.

- Good agreement was found between the trend of the CFD simulation results on the air distribution, and the experimental measures on the air velocity indoor distribution, in particular improving mesh density with finer meshes

- At present full experimental measurements (pressure differences, temperature value at different probe points and total air flow visualisation) are still being carried out.

The cause of quality of measured data not always guaranteed: satisfaction of necessary and possible dynamic, kinetic and geometric similarity laws, confirmation of test repeatability, appropriate calibration of equipment, length scale and temporal scale factor problems.

Results and discussion

- The two (exp.&simul) velocity fields follow the same distribution in the whole building volume with an over-estimation of the air velocity obtained by the simulation in comparison with the experimental situation.

- Results of the air velocity values (exp.&simul) : the mean air velocity values obtained by simulation and integration plot parameters on the surface of the outlet-windows, show a SD of 0.26, in comparison with the experimental data SD of 0.089, evaluated on two days data.

- The exp. mean air velocity value is 0.015 m/s, compared with 0.113 m/s for the simulated one.

- This is very probably due to the real difficulties in taking experimental measurements with PIV on the scaled physical model, checking the position of the camera in front of the rooms and the position/generation of the laser sheet, lighting the rooms, in a plane always perpendicular to the camera.

- The daily indoor air temperature simulated values are quite spatial uniform within the range of 25.11 °C – 28 °C: this is due both to the natural ventilation system connected to the stack effect of the windows and internal ducts (grid system) from the basement to the rooms, and to the thermal inertia of the massive building opaque envelope.

This study shows the ability of the software for modelling natural ventilation flows, driven by thermal buoyancy and stack effects in the building studied.

CFD simulation has advantages due to flexibility, lower realization time and costs compared with experimental measurements of a scaled model performed inside the boundary-layer wind tunnel