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

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Abstract: This paper 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 air flow patterns, air temperature and air velocity distribution inside a historic building in Florence (Italy), the Pitti Palace, were studied by a transient simulation. A three dimensional model of the Palace, that concerns the left wing summer apartments, was investigated using the CFD-FEM Comsol software. The trend of the simulation results, concerning the air velocity and distribution, are in agreement with the experimental ones, obtained by boundary-layer wind tunnel tests at CRIACIV (Inter-University Research Centre on Wind Engineering and Building Aerodynamics) located in Prato (near Florence-Italy). This article shows that CFD with a finite element modelling approach can provide support for the issues involved in the analysis and preventive conservation of ancient ventilation techniques in historic buildings.

Keywords: natural ventilation, transient simulation, cultural heritage, CFD-FEM, wind tunnel

1. Research Aims

Natural ventilation in buildings, generally belonging to bioclimatic design, can provide a comfortable indoor climate and major possibilities for energy saving and reducing energy consumption due to mechanical ventilation and air conditioning systems. Natural ventilation is the most efficient passive cooling system, which was also used in traditional, historic architecture to improve thermal efficiency and indoor building comfort.

Many historic buildings in Florence (Italy) were split between summer and winter apartments. The summer apartment was located on the ground floor and frescoed. Its cool indoor climate was due to the presence of surrounding gardens, and to the high thermal inertia of the ground and wall. Sometimes these rooms benefited from effective natural air-conditioning systems with air channels, gratings, underground openings and rooms and basins for rain water storage.

The Pitti Palace in Florence is one of the most important example of natural ventilation systems in the Italian Cultural Heritage. Some architectural structures, inside historic buildings, are often interpreted as cooling systems. The problem is knowledge of their real working in the past and at present. The application of Computational Fluid Dynamics (CFD) based on the finite element method (FEM) in the Cultural Heritage field, specifically oriented to the knowledge of the natural heat convection systems inside, the evaluation of real possibilities of their reactivation and recovery, is the main aim of the present article. In addition, the information obtained by this study can be useful for the correct design of new naturally ventilated buildings. In this article the analysis of thermal and air flow velocity field inside the apartments studied, was performed by an appropriate three-dimensional model transient simulation. Variations and interaction between indoor and outdoor microclimatic conditions and thermo-physical building behaviour were considered. Results 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 [1,2].

At present full experimental measurements, concerning pressure differences, temperature value at different probe points in the physical scaled model and total air flow visualisation, are still being carried out. 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. So a pulsed laser sheet was used and several pairs of images, logged by means of a high-sensitivity camera, were correlated by a dedicated hardware.

A suitable software permitted to on-line reconstruction of the bi-dimensional flow field by the evaluation of the air velocity in terms of both instantaneous direction and intensity.

Natural ventilation systems existing in historic buildings are conceptually simple, but involving a complex system of physical phenomena and different and various factors, they are really difficult to analyse and predict.

Several thermodynamic and thermo-physical parameters are linearly variable, not correlated, time dependent and not easily evaluated. Wind tunnel tests are time consuming and very expensive and measurement data are normally obtained in only a few points so that they cannot easily be generalised. The multiphysics method of CFD-FEM Comsol software, provides a strong useful tool to address and solve this problem.

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.

2. The Pitti Palace: architectural features and indoor conditions

This research starts from the Palladio's analysis of solar chimneys in the *Quattro libri dell'Architettura* published in Venice in 1570, referring to which a wide ranging survey was carried out to study natural ventilation techniques [3]. The Pitti Palace, and in particular the summer lodgings built for Grand Duke Ferdinando II, during 1621, is one of the examples that was 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 architectural structure of the palace went through three building phases: the building designed for Luca Pitti, the extension designed by Ammannati [3,4] for Duke Cosimo and the project realized by Giulio Parigi for Cosimo II around 1620. The rooms belonging to Parigi's project, located in the left wing, at present occupied by the Silver Museum, are analysed and investigated in the present article. 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).

Today they are covered by mosaic tesserae. In the two small rooms adjacent to the last Museum room the rose gartings are filled with earthenware pieces. Probably this is the final part of a complex natural cooling system designed by Parigi for a single part of the left wing summer apartments. A tunnel very similar to Palladio's wind channels [3], is located in an underground room but today is closed and not accessible.

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. Figs. 1 and 2 show the plant, respectively of the basement and the ground level of the Pitti Palace.

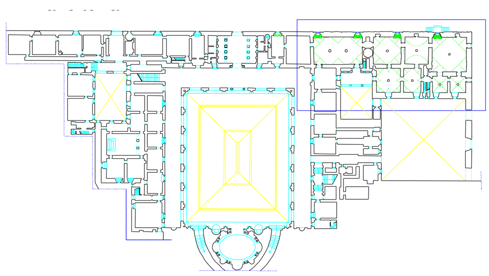

Figure 1 Pitti Palace, ground level

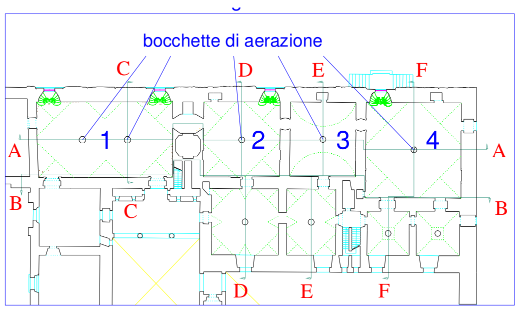

Figure 2 Pitti Palace, ground level, investigated rooms

In figure 2 the ventilation grids inside the investigated rooms are indicated by numbers from 1 to 4.

Figure 3 shows the sketch of the air recirculation hypothesis within the domain of this study.

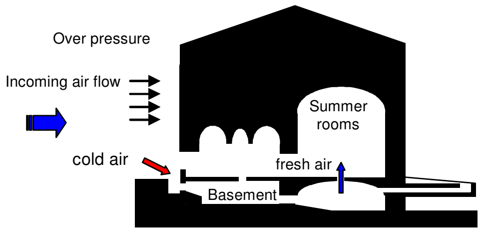

Figure 3 Pitti Palace - the air recirculation hypothesis

3. Modelling and Simulation

A transient simulation was performed on the system limited to the two rooms of the left part of the Pitti Palace, belonging to the summer lodgings, that were also investigated by boundary-layer wind tunnel tests. Fig. 4 shows the air flux displacement from the Boboli Gardens, through the basement and ground floor windows, both North-East oriented, Piazza Pitti through the basement and the ground floor windows, both South-West oriented, and then the domain studied by the transient simulation can also be seen.

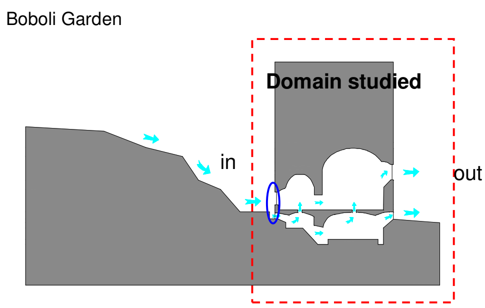

Figure 4 Pitti Palace - the domain studied

For CFD simulation, in particular for three dimensional model simulation concerning natural ventilation, mainly due to the buoyancy effects, difficulties in achieving convergence and how to define boundary conditions at the ventilation openings have been widely reported [5,6,7,8,9].

For the present project the commercially available Comsol Multhiphysics code was used [10]. This code uses the FEM method to solve equations of conservation for the different transported quantities in the flow (mass, momentum, energy, water vapour concentration) and then uses general Navier-Stokes equations to describe fluid flow, deduced for incompressible viscous Newton flow for both Cartesian and axisymmetric coordinates [10]. 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. A three dimensional model of the geometry of the ambient studied was carried out disregarding the surrounding garden, Piazza Pitti and the adjacent rooms. A large domain of computation was generated as a three dimensional full model of the building. 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 945000 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. Time dependent simulation using the system solver “PARDISO” was carried out for the hottest day of the Standard Year in Florence [11]. Solar radiation was taken into account using the corrected external sun-air temperature $T_{sun\text{-}air}$ provided by the formula:

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

This temperature is the one, that the external air must have to exchange the same thermal convective flux, with the wall surface that instead is exchanged by convection and solar radiation. Q_{sun} is the total incidence solar radiation (Wm^{-2}) taking into account different wall orientation and inclination, *a* is the mean hemispheric absorption coefficients of the wall and $h_{convective}$ and $h_{radiative}$ are respectively the convective and radiative coefficient that were assumed to be calculated using the literature values [12,13]. Tab.1 shows the external climatic parameters used.

Conduction, convection and radiation effects, due to the building envelope on the flow, were modelled to carry out the three-dimensional simulation in transient conditions. Thermo-physical properties of different building materials, reported in table 2, were used for heat transfer through the building envelope (the walls, floor and ceiling) and all boundaries of the computational domain, except the ventilation openings, and the doors connecting the adjacent rooms, for which outlet-pressure boundary conditions were assumed, were modelled as no-slip boundaries.

Tab.1 Climatic data of the hottest summer day

hour	External air temp. (°C)	Total horizontal solar radiation (Wm^{-2})	Relative air humidity (%)
1	20.2	0	0.74
2	19.1	0	0.78
3	18.1	0	0.82
4	17.4	0	0.86
5	17.2	9.3	0.88
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
19	32.2	177.0	0.49
20	30.2	0	0.52
21	27.9	0	0.54
22	25.4	0	0.56
23	23.1	0	0.58
24	20.9	0	0.61

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 [13]. The initial conditions for this transient computation were obtained by running the simulation for three days before (259200 s) assuming, for the initial indoor climatic conditions, a uniform internal air temperature of 26°C and 50% of relative humidity, as usually suggested [14,15].

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

4. Results and discussion

Results of time dependent three-dimensional simulation, prove and confirm the real operating of the ancient natural ventilation system and its cooling effect connected to the development of the air flow and the ventilation process from the basement to the rooms of the building. Computational time needed for convergence was 168 hours. The simulation results obtained, follow the same distribution of the air velocity provided by the experimental values measured during an initial short test campaign (Fig.5 and 6).

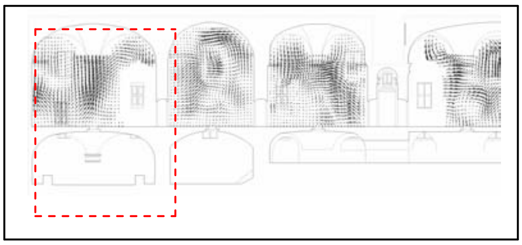

Figure 5 Vector velocity field - experimental – dotted line shows the rooms studied by simulation

Figures 7 and 8 provide the simulation results of the velocity field at 15 h inside the rooms studied, respectively by slice and streamline representation.

Figures 9 and 10 show the air distribution, in particular at the outlet of the inside ducts and through the windows, using bi-dimensional slice representation: temperature distribution is related to mixing capacity of the velocity field that can be evaluated by comparing the heterogeneous air velocity distribution shown in Fig.8 .

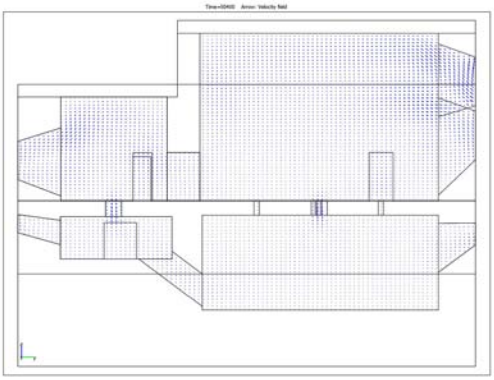

Figure 6 Vector velocity field (Y-Z plane) simulated – July h.15

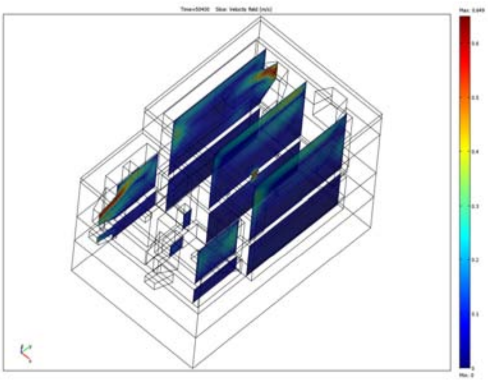

Figure 7 Slice velocity field - simulated –July h.15

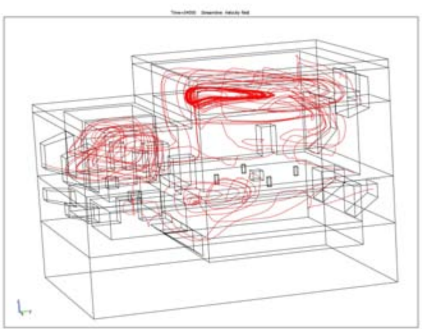

Figure 8 Streamline velocity field – simulated July h.15

This shows the air movement inside the connected spaces, turbulence air distribution and the regions where a recirculation flow occurred.

Moreover, 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.

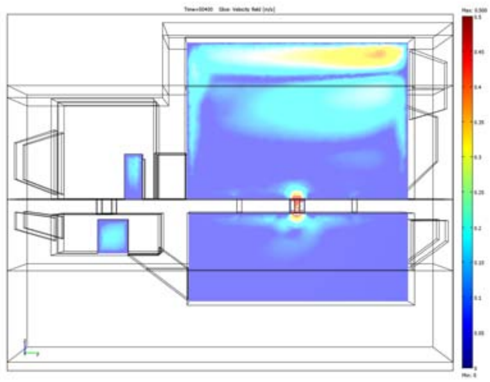

Figure 9 Bi-dimensional slice velocity field – simulated July h.15

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).

Figure 10 Bi-dimensional arrow velocity field – simulated July h.15

The two (experimental and simulated) 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.

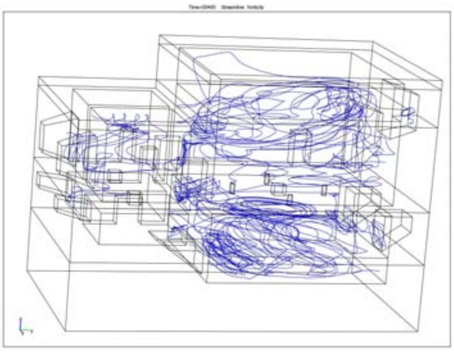

Figure 11 Streamline vorticity field – simulated July h.15

The (simulated and experimental) results of the air velocity values are not easily and directly comparable: the mean air velocity values obtained by simulation and integration plot parameters on the surface of the outlet-windows, facing to Piazza Pitti, show a standard deviation (SD) of 0.26, in comparison with the experimental data SD of 0.089, evaluated on two days data. The experimental 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 the PIV technique on the scaled physical model of the palace, checking the position of the camera in front of the investigated rooms and the position and 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 (the grid system) from the basement to the rooms, and to the thermal inertia of the massive building opaque envelope.

The understanding of the interaction between indoor and outdoor microclimatic conditions, the air temperature and air velocity fields inside historic buildings, then building thermo-physical behaviour, can be important for old building conservation and the study of the better restoring conditions.

The air inlet from the near Gardens into a window-ducts system in the basements of the building compensates the high external air temperature and humidity. Experimental and simulation results confirm the natural ventilation system functioning that can guarantee adequate internal air movement and cooling effect.

5. Conclusions

This study confirms the operating of an ancient natural ventilation system inside a historic building and can offer some suggestions for natural ventilation solutions but also for enhancement and reactivation of these techniques in most historic buildings.

The natural ventilation system studied can ensure stable and quite comfortable internal microclimatic conditions with high summer external temperatures and solar radiation fluctuations.

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.

Differences between the simulated and experimental air velocity values, are mostly due to the difficulties of reproducing natural convection phenomena by small scale tests inside the wind tunnel, using the dry-ice CO_2 tracer and not target wind speed. As a matter of fact, 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, are the cause of quality of measured data not always guaranteed.

This is the reason why a new and wider experimental test campaign is now in progress. CFD-FEM simulation shows the ability of the software for modelling natural ventilation flows, driven by thermal buoyancy and stack effects in the connected rooms of the building studied.

CFD simulation is very promising in terms of flexibility, analytical potential and resolution.

This work shows that CFD, can provide a basic support for the issues involved in the analysis and preventive conservation of ancient ventilation techniques in historic buildings.

The author is at present working on a bi-dimensional transient simulation of the whole system, including the Boboli Gardens, all the rooms adjacent to those simulated for the present work, and Piazza Pitti.

6. References

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7. Acknowledgements

The author is grateful to COMSOL Centre in Brescia (Italy) for support concerning the use of the large scale computer in its Computing Centre.