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Detailed comfort analysis of the cooling system in the 16th century Villa Aeolia (Costozza, Italy)

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Abstract. The villas of Costozza (Vicenza, Italy), built in 16th century, give an example of bioclimatic architecture actual even today. These villas are connected to a large underground cavities network present inside the nearby hills, that can dissipate heat to the ground and provide cool air in summer. Here is analysed Villa Aeolia, still in operation, modelling its natural cooling system in a day of July by using steady-state 3D Fluid Dynamics computations. We focus on three scenarios depending on the outdoor temperature, that follows the daily temperature variations. The simulations let us to know the indoor velocity field and the temperature distribution in the main hall, the Sala Apollinea. Then, we evaluate the global thermal comfort and local discomfort by determining the sensation index Predicted Mean Vote, Predicted Percentage of Dissatisfied and Draught Rating at 1.1 m above the hall floor. This method can easily be implemented in others cases and allows to have a spatial evaluation of comfort and therefore to identify in the different scenarios which are the parameters on which to act in the event of local discomfort.

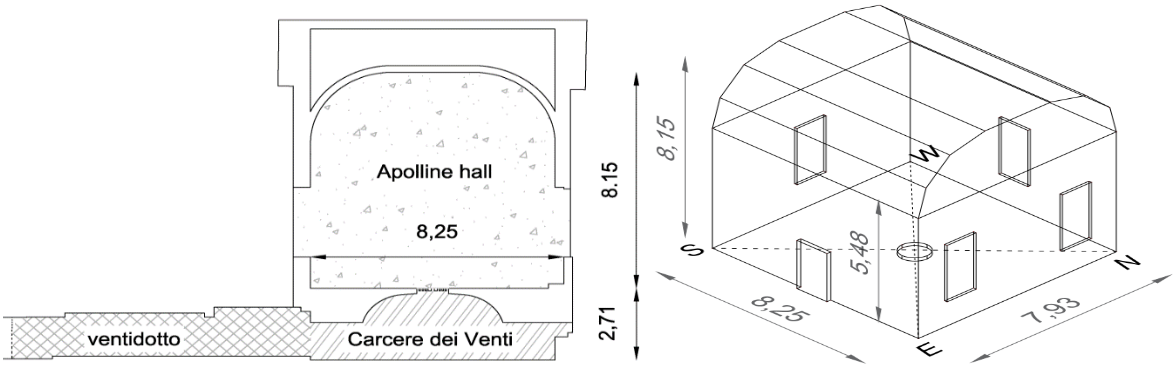
1. Introduction

The territory of Costozza is characterized by the presence of natural or artificial caverns (*the covoli*) inside the hills. Six villas built in 15th-17th centuries are naturally cooled in the summer by the airflow coming from the nearby caverns and distributed by underground ducts (*the ventidotti*). The air comes from the cracks at the top of the caverns, it descends to lower altitudes until to reach the cellars of the villas until to be conveyed into the rooms to cool them. Even if the underground cooling system was known in the 16th century by Palladio [1] and Scamozzi [2], the first experimental measurement of the thermo-hygrometric values in the artificial ducts and in the cellar of the Villa Aeolia is performed on the summer 1981 [3,4] and the second on summer 1990 [5]. Recently others works investigated the ventilation of the villas [6,7] and [8,9] and it is from this last that the input values of this study are used. During these years, the functioning of the cooling system has no longer been monitored, but no change seems to have been made to the ventilation ducts. Therefore we can assume that the system has the same functioning and that it is possible to calibrate it with the data recorded in the past. Villa Aeolia (figure 1) is connected by an underground duct about 135 m long to a cavern. The villa is a pavilion with a square plan composed by the Sala Apollinea, the main hall. The floor of the hall is provided with a marble grating that connects the hall to the basement where there is a cellar called Carcere dei Venti (CDV), figure 2. The Sala Apollinea hall is perfectlty superimposed to the CDV. Scientific literature presents some researches on natural ventilation in historical buildings, using computational fluid dynamic and in field measurement campaigns. Balocco studies examples in Florence and Palermo (Italy) [10,11,12,13] and highlights the need to know the functioning of the ancient natural ventilation devices as those of Palazzo Pitti in Firenze (Italy). Romagnoni consider Cappella degli Scrovegni in Padua and S. Giorgio Castle in Mantua [14,15]. Laurini analysis buildings in San Antonio (Texas) and l'Aquila (Italy) [16,17]. Käferhaus considers Schönbrunn Castle in Vienna

(Austria) [18] and Thomson analyses an Opera House [19]. Also, the studies of D'Agostino [20], Corgnati [21] and Tronchin [22] deal with the CFD simulation of heritage buildings considering different HVAC strategies.

(a) (b) (c)

Figure 1. Villa Aeolia (a), Sala Apolline (b), the cellar, Carcere dei Venti (c)



(a) (b)

Figure 2. Vertical section on Villa Aeolia (a). Geometry of the Apolline hall (b). The dimensions are expressed in [m]. The letters indicate the cardinal points. The room has a vent on the floor that allows connection to the Carcere dei Venti and to the ventidotto [8]

Here we focus on evaluating the hygrothermal comfort obtained in the Apollinea Hall with natural cooling by using the results of CFD simulations. We compute the comfort Predicted Mean Vote index (PMV) [23], the discomfort with Predicted Percentage of Dissatisfied (PPD) [24] and the discomfort of Draught Rate with the DR-index [25]. This method can easily be implemented in others cases and allows to have a spatial evaluation of comfort and therefore to identify in the different scenarios which are the parameters on which to act in the event of local discomfort.

2. Simulation

Three fluid dynamics simulations (case A, B, C) are performed considering the environmental conditions of a typical day in July, the hottest month of the year (by following the meteorological data taken from the reference station located in Vicenza, N 45°34’, E 11°34’). The outdoor temperature, T_{ext}, regulates the flow goes through the floor grid of the villa: at a given outside temperature corresponds a mass flow coming from the ventidotto and passing through the cellar called Carcere dei Venti, CDV . The average values of the air velocity, v_v, coming from the ventidotto has been determined by the study [9] for some outdoor temperature values.

T_{ext} values define possible situations that can occur in a typical July day, where the maximum temperature can reach 33°C, and in the early morning the temperature can fall to 23°C. So, we develop three scenarios A, B and C by varying T_{ext} =23°C, 28°C, 33°C, and respectively the air velocity on the center vent of the hall, v_v=1.14, 1.84, 2.34 m/s. Hence we simulate the variation of the external temperature and its effect on the air flow. The temperature of the flow coming from the underground duct Tv is set 13°C (this value was set to past recordings close to CDV). The temperature of the slab of the hall, the floor temperature Tp is set 16°C, by considering that this was the average temperature in the hall when the cooling system was activated [3]. The temperature of the perimeter walls Tw=23.7°C (corresponding to the average outdoor temperature for the month of July) and the temperature of the roof T_t = (Tw + T_{ext}) / 2.

For *A case study*: v_v= 1.14 m\s, T_{ext} = 23°C, Tt =23.35°C.
For *B case study*: v_v= 1.84 m\s, T_{ext} = 28°C, Tt =25.85°C.
For *C case study:* v_v= 2.34 m\s, T_{ext} = 33°C, Tt =28.35°C.

We choose to 3D model only the Apollinea hall, neglecting the cellar CDV. The geometry has been imported into the software COMSOL Multiphysics (version 4.4) which has a pre-processing module to discretize the computational domain in finite elements. The calculations are solved with the PARDISO solver [26]. The partial differential equations ruling the system are discretized in terms of finite differences and solve in a given number of points of a grid overlapped to the geometrical domain [27]. The mesh is an unstructured grid, composed of 1359439 tetrahedral elements and 8996 pyramidal elements (dimensions: maximum element 0.437 m, minimum size 0.0824 m, maximum element growth rate 1.13m). On the wall-type elements, the mesh is thicker to take into account the viscous effects (the total thickness of the boundary layer is 0.084 m, divided in turn into 5 layers with a stretching factor of 1.2). The model uses wall functions [28] to simulate the contact with the walls. Reynolds Averaged Navier Stokes equations coupled to the k-ε turbulence model are used [29]. The coefficients of the turbulence model are C_{e1} =1.44 , C_{e2} = 1.92 , Cμ= 0.09, σk = 1, σe= 1.3, kv = 0.41. (this turbulence model is chosen for its robustness). The flow is non-isothermal and the fluid is considered newtonian compressible. The model (in steady state) has 2608406 degrees of freedom. The convergence criteria have been reached when all the residual were below 10^{-5}. The monitor points of the air velocity have reached a steady solution. The grid indipendence test has been performed. The model is coupled with the heat transfer equations in fluids. We assign the boundary conditions: an inlet condition on the central floor vent with constant velocity incoming in the domain (v_v), an open boundary on openings (windows and door), *wall functions* on walls, floor and roof. We assign the boundary conditions for the thermal computation: an adiabaticity condition on the south-east wall and on the access door; a constant temperature T_v on the inflow-air (applied to the floor vent), a constant temperature Tw on the three external walls, a temperature Tp on the floor of the hall, a temperature on the roof Tt, an open boundary on windows (the flow can enter into the domain at a temperature equal to the external one Text).

The temperature distribution and the velocity field are shown in figure 3, only for the B case. The jet of the air in the center of the room, first licks at the roof and then goes down along the outer walls, then reaches the floor to be transported up again by the central air jet. The system auto-adjusts: as the external ambient temperature increases, the difference between the outdoor and indoor temperature of the hall increases. For example (see table 1) in C case (Text=33°C) the outer wall and volume temperatures are around 10°C lower than the outdoor temperature and the roof reduces its temperature of 6.45°C (Tt= 28.35°C before passive cooling, $Tt= 21.9°C after passive cooling). The indoor/outdoor thermal difference is lower when the outdoor temperature is minus: the temperature of the roof falls by 3.4°C when the external temperature is 23°C (A case study). During the day the average room temperature ranges from 19.4°C to 21.55°C.

3. Evaluation of thermal comfort

The general thermal sensation is expressed by the PMV and PPD index and the local thermal is comfort by the DR index, that expresses the percentage of dissatisfied with the presence of a draft. *T*hese indicators are calculated at a height of 1.10 m above the floor by using the temperature *ta*, the velocity of the air *va*, the kinetic energy computed in the previous step by CFD simulations at each grid of the mesh. The PMV depends on the activity metabolic energy *M*, the thermal resistance of clothing *Icl* and on the environmental conditions: air temperature *ta*, mean radiant temperature *tmr*, relative air velocity *va* and partial pressure of water vapour *pa.* For the three case studies we calculate the indices for a seating person dressed in light clothes, by setting the metabolic rate M = 1 W/m^2, the mechanical work $W=0$ W/m^2 the clothing insulation Icl = *0.8 clo,* the relative humidity *Ur*= 80*%.*

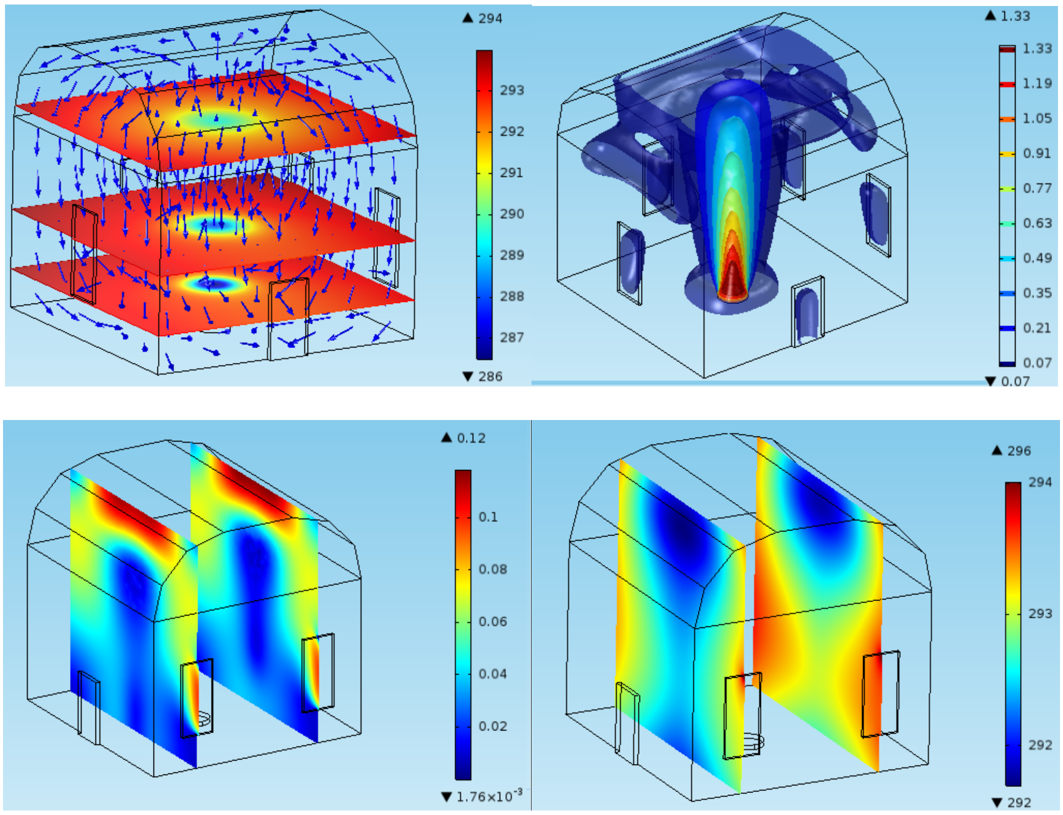


Figure 3. B case study: temperature distribution with air velocity vector field [K] , velocity isosurfaces [m/s], vertical section: velocity magnitude [m/s], temperature distribution [K].

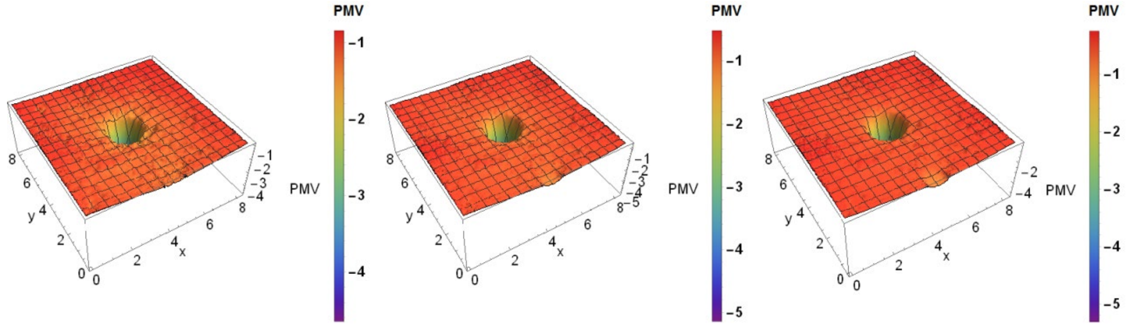
Table 1. Average temperatures calculated for the different geometric elements and zones.

Case study	Text [°C]	Volume [°C]	Roof [°C]	Floor [°C]	NE wall [°C]	SE wall [°C]	NE wall [°C]	SW wall [°C]
A	23	19.4	19.6	19.5	20.2	19.7	20.2	20.4
B	28	20.5	20.7	20.4	21.35 5	20.9	21.4	21.5
C	33	21.5	21.9	21.2	22.4	22.1	22.4	22.4

In A, B, C case studies *pa* is respectively *1803 Pa, 1929 Pa,* 2057 Pa. The mean radiant temperature *tmr* is considered constant over the entire horizontal section of the study, since the temperature of the walls, floor and roof are similar *(*their thermal difference <*10*°C). For the case *A, B, C tmr* = 19.9°C, 21.1*°C* and 22.1*°C*. Figure 4 shows *PMV* values on the horizontal cross section of the Apolline hall at a height of 1.1 m above the floor. In correspondence of the central vent there is a strong discomfort *(*PMV <*-2.5*). The mean values of the PMV are calculated by excluding those in the central hole from where the airflow arrives (table 2*)*. Then, we compute the PPD index (an environment globally acceptable is characterized by *a PPD<10%* or with *-0.5<PMV<+0.5)*. The thermal sensation varies from neutral to slightly cool with a dissatisfaction rate of up to *26.7%* in the case of sedentary activity and external temperature *T*ext=23°C, in fact less comfortable situations occur for lower external temperatures. Concerning the DR (figure 5), above the floor vent the percentage of dissatisfied people is close to *30%* (for all case studies). In the rest of the room there is no risk of draft except close the door where there is a peak at 15% for Text = 33°C.

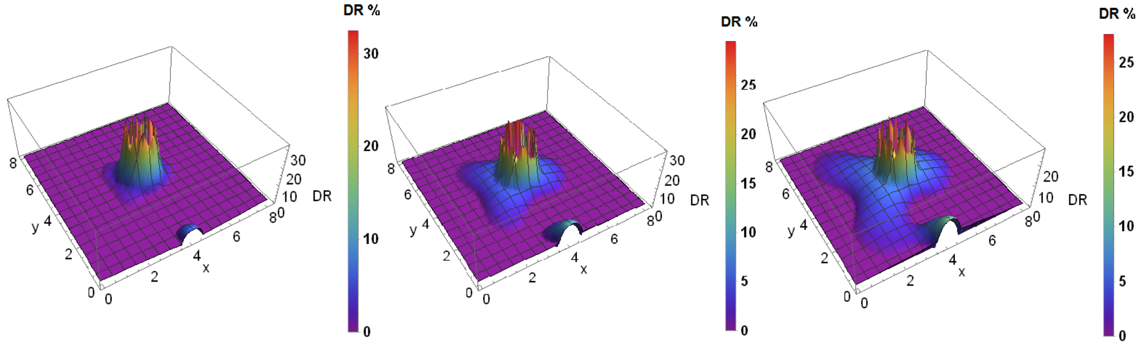
Table 2. Average values of discomfort indices in the room, around the central vent, at a height of 1.1 m above the ground (Icl = 0:8, Ur = 80%, M = 1 W/m^2.

	A, T_{ext}=23°C	B, T_{ext}=28°C	C, T_{ext}=33°C
PMV	-1.01	-0.71	-0.42
PPD[%]	26.79	15.6	8.78



(a) (b) (c)

Figure 4 A case study (DT = 10 K) (a), B case study (DT = 15 K) (b) and C case study (DT = 20 K) (c): PMV for M = 1 W/m^2



(a) (b) (c)

Figure 5. DR, percentage of people dissatisfied: A case study (DT = 10 K) (a), B case study (DT = 15 K) (b) and C case study (DT = 20 K) (c).

4. Conclusions

The airflow rates cool Villa Aeolia with a natural and adaptive cooling system: the airflow increase with increasing of the outdoor temperature. This modulation is comparable to a modern air conditioning system. The comfort analysis shows that the hall is more comfortable during the hottest hours of the day and there is an uncomfortable draught over the marble vent. The comfort is computed in each different position of the hall thanks to the coupling the comfort model with CFD simulations. This methodology is much more suitable than the comfort evaluations made through the outputs of thermal and energy zonal models (where the comfort is computed for each room). The humidity of the air is considered only for the evaluation of indoor comfort, but It would be interesting to investigate its effect on the conservation of the frescoes in the Sala Apollinea as done by [30]. Although for our case the problems of condensation on the walls would not occur in the summer, but probably only in the winter season (in fact usually the system was closed during the winter, perhaps to avoid the condensation). Relative humidity remains high in the room, so it would be desirable to install a dehumidification system to reduce the relative humidity of the incoming air. The system could be put back into operation by inserting adjustable grids to vary the airflow rates coupled to a dehumidification system. Understanding the functioning of these systems is important also to improve the conservation of the villa. Actually, the entry into the pavilion is not possible due to the restoration work of Villa Aeolia. Hence, it was not possible to measure and collect a new experimental database.

In the future, it will be interesting to carry an experimental campaign out to better harmonize the comfort models with the real conditions.

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