Exterior Louvers as a Passive Cooling Strategy in a Residential Building:

Computational fluid dynamics and building energy simulation modelling

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ABSTRACT: The implementation of shading devices is one of the passive strategies to improve indoor thermal conditions during summer. They can obstruct direct solar radiation while permitting wind flow inside the building. Therefore, its use implies two passive interventions for indoor thermal comfort: solar protection and natural ventilation. This study focuses on the implementation of exterior louver systems and the simulation, evaluation and improvement of indoor thermal comfort in an existing modern residential building in Palermo, Sicily. The implementation of the louver systems, the natural ventilation strategies and the evaluation and quantification of the (dis)comfort is performed by coupling Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES) calculations. Values of indoor air speed and pressure coefficients are obtained from CFD calculations and further used as input in BES calculations and comfort analysis. The results show, for this particular case, that overheating problems could be improved by passive means by the application of several strategies like the use of existing balconies with external louver systems and whole day natural cross ventilation.
Keywords: passive design, shading devices, summer comfort, residential buildings

INTRODUCTION

The implementation of shading devices is one of the passive strategies to improve indoor thermal conditions during summer. More specifically, exterior louver systems are considered among the most effective shading devices [1]. They can obstruct direct solar radiation while permitting wind flow inside the building. Therefore, its use implies two passive interventions for indoor thermal comfort: solar protection and natural ventilation. On the other hand, re-use and renovation of buildings are core strategies towards a rational environmental policy. They preserve not only the city memory and cultural values but also diminish the use of non-renewable natural resources and save energy. However, many after-war modern buildings in Europe have poor climatic design which can lead both to uncomfortable indoor conditions during hot summers and to a high energy consumption by cooling.

This study focuses on the implementation of exterior louver systems combined with natural ventilation strategies [2, 3]. Numerical and energy simulations are performed in order to evaluate and propose improvement solutions concerning thermal comfort inside an existing modern residential building in Palermo, Sicily.

METHOD AND CASE STUDY

The implementation of the louver systems, the natural ventilation strategies and the evaluation and quantification of the (dis)comfort is performed by coupling Computational Fluid Dynamics (CFD) [4] and Building Energy Simulation (BES) calculations [5,6]. Values of indoor air speed and pressure coefficients are obtained from CFD calculations and further used as input in BES and comfort analysis. The CFD turbulence model and grid type were verified using wind tunnel data from literature. An apartment was chosen at an intermediate floor for the natural ventilation and thermal comfort analysis. The results are based on the effect louver systems and natural ventilation have on indoor thermal comfort by using the Predicted Mean Vote (PMV) method [7] which considers both environmental (air temperature, mean radiant temperature, relative humidity and air speed) and personal (clothing resistance and metabolic rate) parameters.

Climatic conditions The apartment building is located in Palermo, Sicily near the harbour called “La Cala”. Palermo is 38º 10' north 13º 6' east. It has a Mediterranean climate with moderate warm temperatures during summer (mean minimum and maximum equal to 23.6 ºC and 27.1ºC respectively) but with relative high values of relative humidity (RH) (mean minimum and maximum equal to 67% and 78% respectively) due to the influence of the mountains which promote rain and also the influence of the sea breezes. The selection of typical weather conditions is crucial in computer simulations for performance predictions [8]. In this study, the Test Reference Year (TRY), obtained from observed meteorological records [9] is used as a source for evaluating the thermal performance of the selected building.

Building characteristics The building was built in the 1970's, it has seven floors and its main facades are ENE-WSW oriented. The WSW side faces the city separated by a wide road while the ENE side faces the old fortress and the sea. However, in this study the building will be considered as a typical block with main facades oriented north (upwind) and south. The building, which is 25 metres high, 63 m long and 15 m wide, can be considered free-standing since there are no big obstacles around it (Fig. 1).

The building has a concrete skeleton structure with massive lime sandstone blocks and it has a flat roof. The exterior walls (0.4 m) consist of two layers of plaster at interior and exterior side and two layers of limestone bricks with an intermediate air cavity (U-value = 1.93 W/m^{2}k). The interior walls inside the apartment (0.1 m) are composed by two layers of plaster and a layer of limestone bricks (U-value = 4.56 W/m^{2}k). The building has a high thermal capacity. The wall to window ratio is 30%. Each floor has six individual apartments. Each apartment has two living rooms with balconies oriented to both facades, a kitchen, a storeroom, two bedrooms, a bathroom and a central hall. Some of the apartments have an interior ventilation duct (patio). The ground and first floor is reserved for shops, workplaces, business accommodation and the entrance halls. In order to reduce the number of variables an apartment was chosen at an intermediate floor (4th floor) for the natural ventilation and thermal comfort analysis.

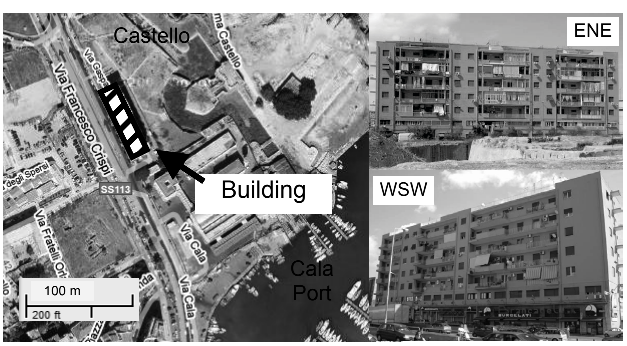

Figure 1: Location of the building near La Cala harbour in Palermo (from Google Map) and view of the main facades (fieldwork picture).

The internal gains are also taken into account and include the gains of the occupants, heat sources, lighting and other electrical equipment, which can be specified through the use of schedules. Given the fact that this is a large apartment with two bedrooms, we considered two types of 'average' families with four members: two parents (at home all the time, or outside during working hours) and two children (at school). The lighting and other electrical equipment are directly related to the family's schedule.

Passive strategies Two main passive strategies: natural ventilation and exterior shading devices are proposed in order to test their influence on the thermal conditions inside the apartments.

The ventilation strategies are described as follows:

- only infiltration through cracks, closed windows.
- cross ventilation, windows and doors opened during the whole day.
- with infiltration and night ventilation, windows are opened from 22h till 8h.
- with infiltration and windows opened from 17h till 24h, (typical for families at work/school).
- with infiltration and mixed ventilation, the windows on the north are open from 12h till 17h (single-sided ventilation) and all the windows are opened from 17h till 24h (cross ventilation).

The shading strategies for vertical louvers are described as follows:

- no balconies and no vertical louvers;
- balconies but no vertical louvers;
- no balconies but with vertical louvers;
- balconies and vertical louvers.

The exterior shading consists of a vertical system of louvers with horizontal slats (Fig. 2). In this paper we refer to it as vertical louvers. In order to simplify the modelling, the slats are considered flat. Their dimensions are 10 cm wide, 1 cm thick and separated 10 cm from each other.

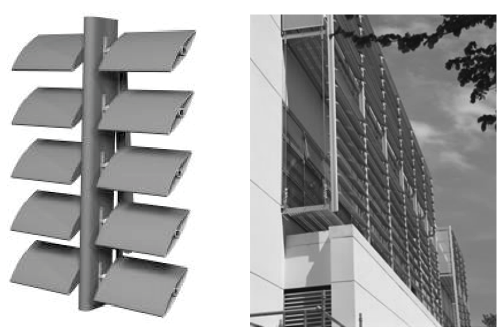

Figure 2: Exterior louver system (vertical louvers) which are analysed in this paper. (Reynaers Aluminium B-100 [10]).

CFD validation Because there were no measurement datasets available for the actual dimensions of the analysed building, the model validation was conducted for a block with similar building configuration. Here, the wind-tunnel experiments data from the University of Hamburg (CEDVAL) were used [11]. The experiments were conducted at a scale of 1:200 in a boundary layer wind tunnel of 1 m height, 1.5m depth and 4 m length. The model height is 0.125 m (H, height) for actual building dimensions of 25 m (H), 20 m (0.8H, depth) and 30 m (1.2H, Length). The measured mean wind speed profile is a logarithmic law with a gradient wind speed U_{ref} = 0.1 ms^{-1}, aerodynamic roughness length y_0 = 0.0007 mm, displacement height d = 0 mm, power low exponent α = 0.21 and a friction velocity u* = 0.377 ms^{-1}.

The numerical simulations of these wind tunnel experiments were first performed at model scale in order to eliminate errors due to scale effects. Then, simulations were performed at the building scale using the selected turbulence model. Three-dimensional (3D) hybrid meshes were elaborated by using structured quadrilateral cells (174 500). The grid resolution was based on grid-sensitivity analysis. The commercial CFD code Fluent 6.3.22 (2006) was used to solve the 3D (RANS) equations and the continuity equation. Closure was obtained using the realizable k-ε model [12]. Figures 3a and 3b illustrate the flow pattern from the wind-tunnel experiment and the CFD simulations respectively by means of velocity vectors in a longitudinal-section of the wind tunnel. Figure 4 shows the velocity profiles at the upstream side of the block for both the experiments and the CFD simulations.

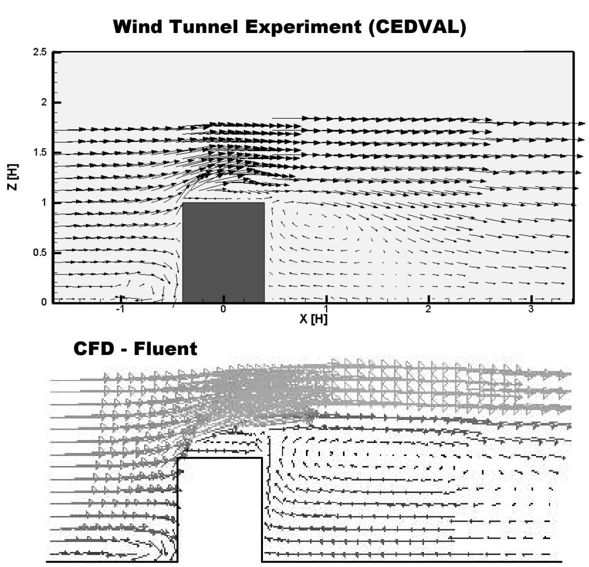

Figure 3: Velocity vectors on a longitudinal-section (a) wind-tunnel experiment (CEDVAL), (b) CFD simulations.

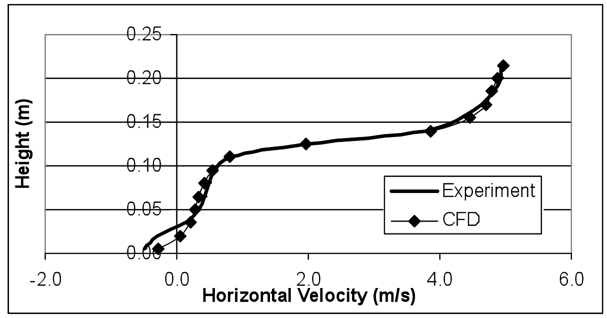

Figure 4: Velocity profiles at the upstream side of the block for the experiment (CEDVAL) and CFD simulations.

The results of the validation indicate that the used CFD model can predict quite accurately the velocity profiles close to the upstream and downstream facade (9% error). The downstream vortex, however, is not well predicted due to the problems, already reported in literature [13], of the k-ε turbulence model to predict the turbulent flow on the re-attachment area. Nevertheless, by comparing the pressure coefficients on both facades with measured values on a similar block in another wind-tunnel test [14], they showed to be acceptable for natural ventilation analysis. Based on the outcome of the validation study, the numerical model (RANS equations and realizable k-ε model) was considered suitable for the analysis of the flow conditions on the building model.

RESULTS

The results from the CFD and BES simulations are summarised and presented in the following paragraphs. A representative summer week from 6 till 12 August was selected for the analysis. First the result from the different strategies of natural ventilation is briefly presented. Then, the implementation of the vertical louver system on CFD as a porous media is explained. Finally, the influence of both natural ventilation and shading devices on thermal comfort is analysed in terms of Predicted Mean Vote (PMV).

Natural ventilation Here the results from the five ventilation strategies are compared and no louver systems are considered in these simulations. All situations are compared for two representative rooms, the living room on the north and the middle living room on the south facade. Figure 5a illustrates air velocity vectors on a top view of the apartment at 1.5m from the floor level for the cross ventilation case. Figure 5b illustrates the corresponding average values of air speed for different room's locations. The wind speed at the weather station has an average value of 3.8 ms^{-1}.

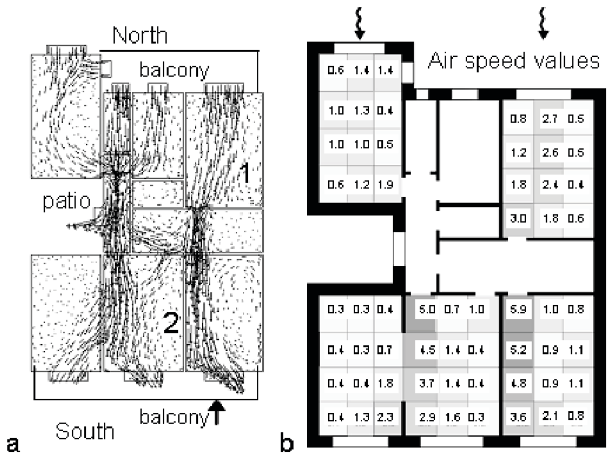

Figure 5: (a) Air velocity vectors, top view of the apartment at 1.5m from the floor level, 1 and 2 indicates the living rooms at the north and south facades respectively, (b) air speed values (m/s) for each room with 12 artificial subdivisions (cross ventilation case). The wind speed at the weather station has an average value of 3.8 m/s.

Concerning the five ventilation strategies, the situation with only infiltration gives the worst results due to the insufficient ventilation which can not remove the heat gains. Therefore, indoor temperatures are around 5ºC higher than the exterior air temperature (t_{ext}). On the contrary, the best ventilation strategy for the summer conditions is the one where the windows are opened during the whole day. Here the air temperatures are lower (0.5-1ºC higher than t_{ext}) due to the heat removed from ventilation, and the indoor air speed is higher which provide a cooler sensation and thus, lower PMV values. However, for some specific areas (e.g. close to door in room 2) very high air speed values are predicted which can provoke uncomfortable conditions. For the case in which the family are out during the day, the best option is to open the windows once they arrive home (17h in this analysis).

Effect of exterior vertical louvers on ventilation

Louvers protect direct solar radiation but can also obstruct the airflow through windows according to the type, dimensions and slat inclination. Therefore, in order to predict the effects of exterior louvers on the indoor air speed and distribution and also on the thermal comfort, a model of the exterior louvers were developed. The exterior louvers can be modelled in CFD in different ways. One way can be constructing a mesh which includes each slat separately. But this method which can be quite accurate can also be very laborious and time consuming. The second way is by implementing a porous medium in the area of the shading device which should offer the same resistance to the airflow as the actual louver system [15,16]. The second method is the one used in this work (Fig. 6).

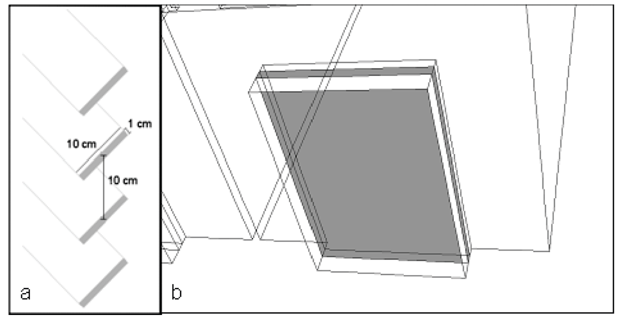

Figure 6: Shading devices (a) dimensions of the vertical louvers, (b) porous media.

The static pressures at the windows were found by constructing 3 two-dimensional (2D) sections through the apartment. In these 2D models, the pressures at the windows were calculated. An average static pressure was taken over the windows and used to set the pressure inlets and outlets. The direction vectors of the porous medium have to be set. For the louvers on the living room on the north, this give a direction_1 vector (0, -1, 1) which indicates a flow perpendicular to the slat thickness (0.01m, lowest resistance) and direction_2 vector (1, 0, 0) which is the flow parallel to the slat thickness (highest resistance). Two simple CFD models of a single slat at 0º and 45º were constructed to get the inertial resistance coefficients of the porous medium. The slats are considered flat to simplify the geometry of the louvers. The obtained inertial resistance coefficients are 3.78 m^{-1} and 31.72 m^{-1} for the direction_1 vector and direction_2 vector respectively for the slats at 45º. Then the open volume fraction of the medium (porosity) is calculated, being equal to 0.9. With these coefficients and the porosity of the louver system the porous medium is implemented for each exterior louver at inlet and outlet. For more details we refer to [2].

Figure 7 shows the effect of the vertical louvers on the airflow direction and air speed for the living room at north which is the upwind facade (inlet). As expected, the average value of the air speed in a room is the highest for the situation without louvers. For the case with louvers which slats are at horizontal position (0º) the air speed is very similar in comparison with the case without louvers. On the other hand, the average values of the air speed are the lowest for the situation with the slats at 45º due to the higher resistance to the flow. However, the tilted slats provoke lower air speeds, in comparison with the case without louvers, at the positions with higher air speeds (path between the inlet window and outlet door) and higher air speed values at the positions with lower air speed inside the room. This means, probably due to a redistribution of the pressure at in- and outlet, that there is in general better airflow distribution inside the room when there are tilted louvers on the windows.

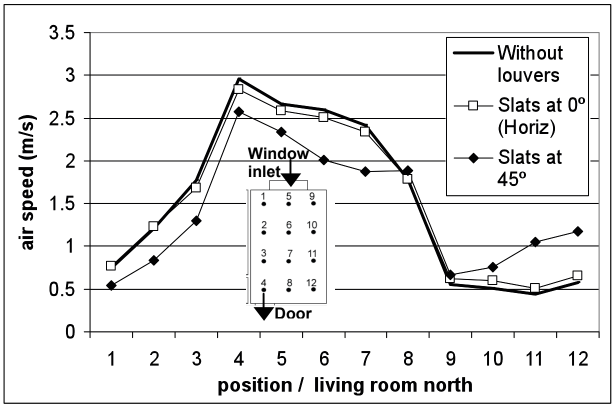

Figure 7: Average value of air speed for each position inside the north living room for cases without louvers, with slats at 0º and at 45º. The room scheme indicates the position of the analysed points (till 2m height) inside the room.

Similar results are obtained for the other rooms facing north but with less difference between the cases with and without louvers. For the rooms at the south facade, the louvers with slats at 45° provoke lower air speeds, in comparison with the case with no exterior louvers, on the areas with higher air speed, (path between inlet door and outlet window), but very similar values in the positions where air speed is lower inside the room.

Combined natural ventilation and shading devices

The combined effect of natural ventilation and shading devices is analysed in this section. BES programs are used to predict indoor thermal conditions and thermal comfort. Simulation verification was performed by comparison of results between EnergyPlus 1.4 and TRNSYS 16 [3]. The values of indoor air speed and pressure coefficients on facades are taken from the CFD simulations. Windows and internal doors are considered open all the time (cross ventilation) for the case with exterior louvers which have 45º of inclination. However, in order to confirm some results concerning the influence of shading devices, several simulations were performed considering only infiltration (closed windows).

Table 1 shows the percentage of time during the selected week in August in which thermal comfort is reached on the living room at the north and south facade for the four different shading strategies with vertical louvers. PMV method is used for the comfort analysis and comfort was considered for the interval -0.5 ≤ PMV ≥ 0.5 in the seven points scale which means 90% of people felt a comfortable condition. The situations in which PMV value is below the comfort level, i.e. below -0.5, are not taken into account on these percentages because in actual cold thermal conditions the inhabitants close the windows to reach acceptable comfort levels. The best situation is when both shading strategies, the use of balconies and exterior louvers, are applied.

Table 1: Percentage of time in which thermal comfort is reached according to the shading strategy (balconies and vertical louvers) for the living room at the north (N) and south (S) facade. PMV interval -0.5 ≤ PMV ≥ 0.5.

Shading strategy	Percent of time with thermal comfort (%) Living N	Living S
No balconies, no louvers	55	46
balconies, no louvers	80	76
No balconies, louvers	91	90
Balconies and louvers	96	96

The worst situation is without balconies and without exterior louvers. This is more evident on the south facade where solar radiation is higher than at the north side. The difference in maximum temperature between the situation without any shading and the situation with balconies and vertical louvers is about 3°C for the north side and 5°C in the south. From the PMV values, it can be argued that in this context, the influence of the air speed on thermal comfort is higher than the influence of the shading in the living room on the north. On the contrary, for the living room in the south, the shading effect appears to be dominant. This is noticeable when two ventilation strategies, (cross ventilation and only infiltration) are compared. Here the difference in terms of thermal comfort are lesser than with the application of the different shading strategies. However, according to these results and bearing in mind the limitations of the BES calculation methods concerning the shading devices [3] (e.g. long-wave radiation and convection from the slats to the interior are not considered on TRNSYS model), for both facades, the application of exterior louvers alone is more effective in terms of thermal comfort than the use of balconies alone.

DISCUSSION AND CONCLUSIONS

In this paper the implementation of exterior louver systems and the simulation, evaluation and improvement of indoor thermal comfort in an existing modern residential building in Palermo is performed. Several ventilation and shading strategies are considered and the influence of exterior louvers (vertical system) on the indoor airflow and air speeds is also analysed by using a simplified modelling method in the CFD simulations. The use of CFD calculations is required for the prediction of indoor air speed which is a necessary parameter for comfort calculations. CFD validation was first performed by comparing velocity profiles with measured values from a wind-tunnel experiment performed at the University of Hamburg (Meteorological

Institute) (CEDVAL). The results indicate that although the downstream vortex is over-dimensioned by the CFD simulations, it can predict quite accurately the velocity profiles close to the upstream and downstream facade which are of importance in this study. The numerical model (RANS equations and realizable k-ε model) was considered suitable for the analysis of the flow conditions on the building model.

From the CFD simulations of several ventilation strategies it can be concluded that opening the windows and interior doors during the whole day gives the best results for the indoor climate and comfort conditions. In the analysed apartment, the second best method is to open the windows as soon as people come home. Since ventilation potential is high around the isolated building, and the air temperature is most of the time below extreme values (<30ºC) the ventilation is very effective on removing internal gains and providing indoor airflow which produce a cooling sensation on the inhabitants.

The influence of the exterior louvers (vertical system) on the indoor airflow is negligible when the slats are at horizontal position (0º) in comparison with the situation with no shading devices on the windows. When the slats are at 45º, there is a reduction on the air speed close to the inlet (windows at north facade) and close to the outlet (door). On the other hand, the louvers provoke an increase of air speed, in comparison with the case with no shading devices, in the areas with lower air speed. Therefore, we can conclude that the use of exterior louvers with variable inclinations is beneficial for the indoor airflow distribution and a solution for the uncomfortable shafts inside the apartment.

The use of exterior vertical louvers in combination with natural ventilation (cross ventilation or only infiltration) was also analysed in terms of thermal comfort. The results indicate that the temperatures were the lowest and the thermal comfort (PMV) closest to a comfortable condition for the situation in which both a balcony and horizontal louvers were applied. The second best situation was the one with only vertical louvers. Notice that, in this study, the influence of louvers on the indoor daylight was not evaluated. The natural ventilation strategy is more effective for the north oriented rooms, while the shading strategies were more effective for the southern rooms.

Further research should be conducted in order to improve the implementation of calculation models concerning exterior louvers in the BES programs. Reflections between specular slats should be considered as part of BES programs or by coupling them with more specialised stand-alone programs. This will permit an integral analysis in which both thermal and daylight conditions are considered.

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