Integration of Experimental and Simulation Computer Fluid Dynamics to Improve Natural Ventilation in Buildings for Hygrothermal Comfort and Energy Savings

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ABSTRACT: Buildings consume nearly half the global annual energy use that comes mainly from the burning of fossil fuels, which provokes the emission of greenhouse gasses (GHG), and consequently global warming and climate change, among other consequences. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) confirms and ratifies the necessity for immediate and sustainable actions to reduce the burning of fossil fuels. Buildings play an important role for this to come about, as they are responsible for almost half of the CO2 emissions. One strategic area for this approach to be applied is in providing effective natural ventilation in buildings to achieve the maximum possible comfort conditions for the occupants at the minimal consumption of energy. The objective of this research is focused on the integration of experimental and simulated fluid dynamics techniques in buildings, aimed at providing sustainable educational design tools for engineers and building practitioners. The results indicated that the suitable use of experimental and simulation techniques for analysis and evaluation of natural ventilation are useful tools to achieve a significant reduction on energy consumption whilst improving the occupant´s hygrothermal comfort and the environment, and to promote sustainability.

Keywords *Thermal comfort, Natural Ventilation, buildings, hygrothermal comfort, energy savings.*

ISBN: 978-85-92631-00-0

1. INTRODUCTION

The supply and control of natural ventilation is essential in all type of buildings. The use of natural ventilation plays a crucial role in the design of buildings for hygienic reasons and for providing hygrothermal comfort conditions to the occupants, as well as for achieving energy savings and improving the environment.

Methods for evaluating natural ventilation in buildings include mathematical and computer models as well as experimental procedures. Three-dimensional physical simulators, in the form of wind tunnels are practical and useful tools for studying air movement patterns in and around buildings experimentally in architectural and urban projects. The utilization of wind tunnels can provide two components: Visualization of airflow patterns in and around buildings and measuring of wind pressures and speeds. These two components are complemented with computer fluid dynamics (CFD) that is computer simulations for visualization and measuring pressures and wind speeds.

Nowadays, most modern buildings incorporate architectural styles and materials that ignore the local climate as well as its cultural and traditional factors. This is the predominant case of many contemporary buildings located in hot climate regions. As a result, such buildings are highly dependent on mechanical and electrical systems to control the indoor environment. This situation causes the consumption of large quantities of energy and thus high running costs for both artificial lighting and air-conditioning systems (AC), associated with problems of occupants' discomfort, both hygrothermal and visual, among others.

2. POTENTIAL OF PASSIVE COOLING TECHNIQUES

The bioclimatic strategy of "Passive Cooling" is an approach that focuses on heat gain control and heat dissipation in a building aimed at improving the occupant's hygrothermal comfort whilst reducing the energy consumption. It works either by preventing heat from entering the interior (heat gains prevention) or by removing heat from the building (heat dissipation or natural cooling). This later cooling technique utilizes on-site energy, available from the natural environment, combined with the architectural design of building components and the building envelope, rather than mechanical systems or HVAC, to dissipate heat from the internal architectural spaces. It has been demonstrated in previous studies that the implementation of passive cooling techniques in buildings with high thermal cooling loads is a promising alternative to contribute to solve high external and internal heat gains and high energy consumption patterns, occupants' thermal discomfort and health conditions whilst reducing environmental damage problems (Artmann, et al, 2007; Blondeau et al., DeKay, et al. 2014; García Chávez, 2015; Givoni, 1994 Santamouris et al, 1996, Lechner, 2009; Kwok et al., 2014). Likewise, the results of traditional or vernacular architecture, with simple common sense solutions in different regions of the world, have demonstrated the effectiveness to respond to the specific climate conditions aimed at achieving hygrothermal comfort conditions of building´s occupants, whilst reducing the energy consumption and energy demand of conventional energy fossil fuels for operation and maintenance of the buildings, as well as decreasing the emission of greenhouse gasses (GHG) to the environment (Givoni, 1994; Fernandes et al , 2015).

Therefore, passive cooling strategies offer real opportunities for improving the occupants' ambient comfort conditions in buildings located in prevailing hot climates and/or during overheating conditions, whilst reducing the energy consumption due to the use of mechanical systems for space climatization (AC).

ISBN: 978-85-92631-00-0

3. NATURAL VENTILATION AS A PASSIVE COOLING TECHNIQUE TO PROVIDE HYGROTHERMAL COMFORT IN BUILDINGS

Natural ventilation is one of the passive cooling techniques which can be applied as a powerful bioclimatic strategy to provide hygrothermal comfort to occupants of buildings. Natural ventilation can be defined as the desirable air exchange (such as through open windows horizontal or sloped openings, among other building elements), capable of cooling the space, the structure, and/or the occupants' bodies.

In this research, the natural ventilation strategy was selected for investigation applying experimental techniques in a wind tunnel and simulation CFD techniques to assess the performance of typical building configurations, aimed at providing sustainable educational design tools for schools of architecture and engineering, as well as design alternatives for engineers and building practitioners. The results of this research indicated that the suitable implementation of these techniques in the design and construction of buildings in different climates could lead to a decrease on energy consumption whilst reducing environmental impacts and improving the occupant´s hygrothermal comfort and the environment.

4. USE OF A WIND TUNNEL TO ASSESS THE PERFORMANCE OF CONVECTIVE COOLING IN THREE-DIMENSIONAL PHYSICAL MODELS

Previous research work has identified the usefulness of wind tunnels for assessments of naturally ventilated structures (Vickery, 1981; Tolentino et al, 2008. 2015). This work investigated the potential of natural ventilation techniques in typical building configurations aimed at reducing energy consumption whilst providing hygrothermal comfort conditions for real building occupants. For the assessments of these techniques perplex three-dimensional physical models were applied through the experimental work, using a wind tunnel, which served to demonstrate the advantages of using natural ventilation (Figures 1, 2 and 3). The perplex scale models were introduced in the wind tunnel for investigation of their performance under some conditions, meant to enhance natural and optimize ventilation real buildings.

Figure 1. 3D Physical scale model 1 showing section frame with Thin wires for visualization technique

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Figure 2. 3D Physical scale model N1 in wind tunnel operating at 2 m/sec speed, showing section frame with thin wires moving for visualization technique

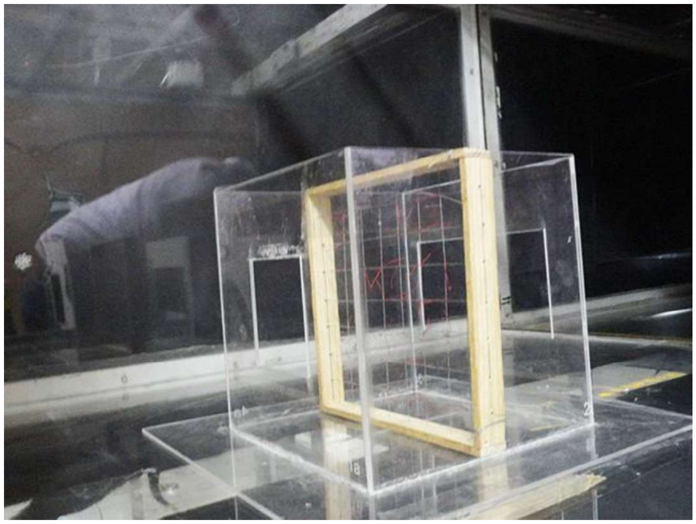

Figure 3. 3D Physical scale model N2 showing section frame with thin wires for visualization technique and hot wire anemometer for pressure and wind speed measuring

The wind tunnel utilized for the experimental work is located at the Laboratory of Applied Thermal and Hydraulic Engineering.

It is an open circuit wind tunnel with a suction and pressure test section. The airflow is generated by a centrifugal fan driven by a 74.6 kW (100 hp) electrical motor controlled with a variable frequency drives, to get different velocities in both test sections. The highest wind velocity in the suction test section is 65 m/s. This velocity depends of environmental conditions like temperature, pressure and humidity (Figure 4).

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Figure 4. View of the wind tunnel used during the experiments

The test section has a rectangular cross section of 0.8 meters by 0.6 meters, a variable length of 4.0 meters. The wind tunnel has a settling chamber to have a good flow quality in the test section. The components are a bell mouth follow by a honeycomb grid with a cell size of 10.5 mm, thickness of 0.2 mm and a length of 85 mm. Once the flow passes through the honeycomb grid, there are five screens of 20 meshes, wire diameter of 0.23 mm and an open ratio area of 0.67, to reduce the velocity fluctuation in the test section. At the end of the settling chamber, there is a contraction with an area ratio of 9:1, a length of 1,680 mm manufactured with plywood. Details of the design of the wind tunnel are shown in a previous work [12]. The flow quality in the test section was verified by measurement of velocity profile, turbulence and boundary layer in the test section by means of a hot wire anemometer. The results demonstrated that the velocity variations in the test section are less than 1% and the turbulence intensity is less than 0.5% in (Tolentino et al, 2015, Murakami, (1991).

5. METHODOLOGY

5.1 Instrumentation

The instrumentation used to get the velocity distribution was a constant temperature hot wire anemometer, 90C10 model. The probe 55P11 was used to measure the velocity and turbulences intensity. The probe was calibrated in a velocity range from 0.5 m/s to 50 m/s. Frequency and time sample were 30 kHz and 30 s for all measurements.

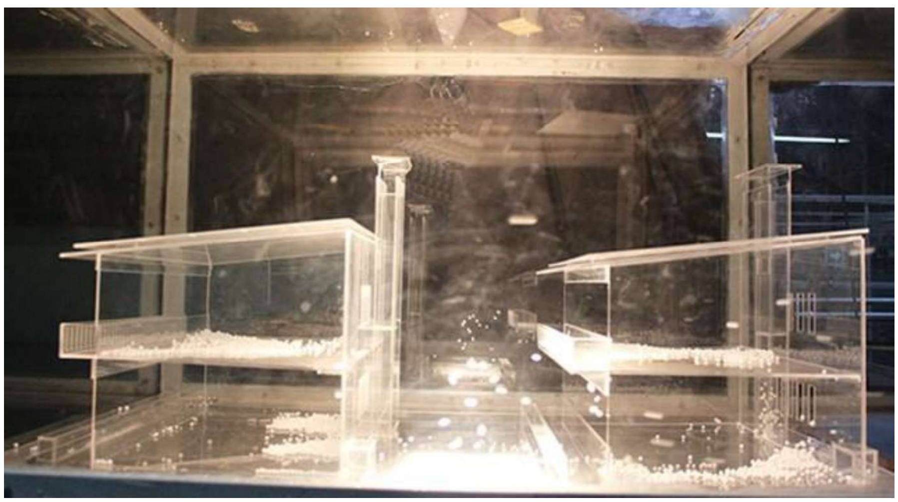
The probe was moved by a three dimensional traverse system. The traverse is outside the tunnel in order to avoid the blockage effect. Pressure, temperature and humidity relative were also measured during the experiments by means of a local on-site meteorological station. Data velocities collected were reduced to get the turbulence intensity [%] in every point measured.

ISBN: 978-85-92631-00-0

5.2 Development of the Experimental Work

Before the implementation of the experimental work, the design variables to be analyzed were established. During the first set of the experimental work, cross ventilation was assessed in the two scale models. Different visualization techniques were applied and subsequently pressure and wind speed were measured. A third scale model was subsequently evaluated using also visualization techniques and measurements of pressure and wind speed. This scale model included evaluation of direct wind and by means of the differences in temperature and pressure of the air. This natural ventilation strategy is called buoyancy or "stack effect" or "chimney effect". The effectiveness of both cross ventilation and stack effect were demonstrated in the scale models evaluated (Figures 1, 2, 3 and 5).

Figure 5. 3D Physical scale model N3 of a real educational building in wind tunnel operating, showing visualization technique of small polystyrene spheres



For the monitoring of the air velocities, three measuring points were located within the physical scale models at 120 cm height. Hot wire anemometers were used for the measurements in the physical model whilst maintaining the required velocity, controlled by the electronic speed system of the wind tunnel. For visualization of air patterns inside the physical model, the techniques used to identify the air movement was by means of a a) Section frame with thin wires; b) Small polystyrene spheres; and c) Smoke flux fine at different heights to provide a complete scan of the scale models. High resolution digital video and fixed pictures were applied to capture air movement pattern images (Figures 2, 5 and 6).

The average ambient temperature range recorded during the experiments was from 22° C to 23 ° C; the relative humidity varied from 62% to 63%, and the atmospheric pressure was stable at 79.8 kPa. The indoor air speeds within the model were measured as a percentage, relative to the external wind velocity at window level. Since the physical models tested had no curved surfaces, the air flux was discharged from the borderlines and thereby the results become independent of the Reynolds Number. Therefore, this outcome is a valid approximation, as the comparisons of velocity percentages of the model investigated relative to the air flux in a 1: 1 real case, and therefore, it is a reliable parameter for analogy.

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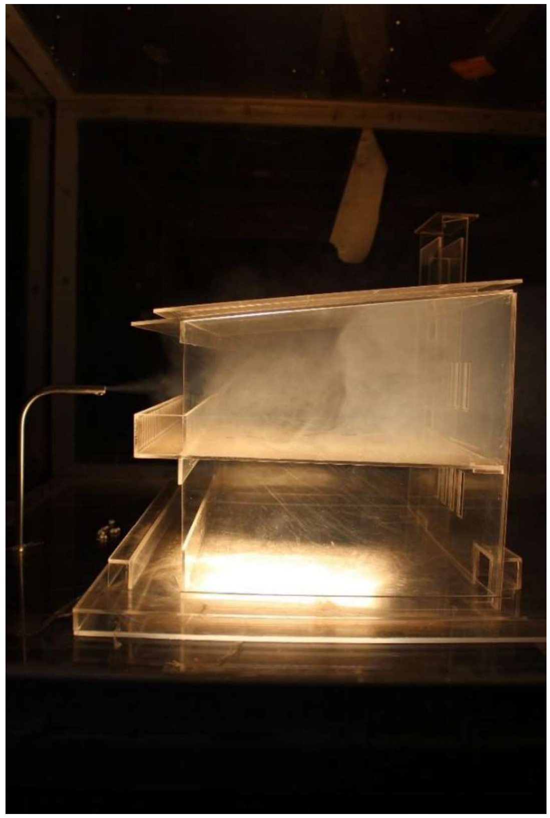
Figure 6. 3D Physical scale model N3 in wind tunnel operating, showing visualization technique of smoke at different heights



6. ANALYSIS OF COMPUTER FLUID DYNAMIC RESULTS

Computer Fluid Dynamics (CFD) techniques were applied for the three models investigated in the experimental work in the wind tunnel. The results of the CFD analysis have shown a close approximation of the performance of air movement both outside and inside the analyzed models (Figures 7, 8, 9).

In model N1 model (for cross ventilation analysis), it can be seen an increase of air velocity inside the space. In model N2, with a 2:1 ratio, i.e. greater outlet opening relative to the inlet opening, it can be observed a more uniform upwards widespread air movement useful to promote heat gains and to dissipate polluted indoor airborne particles of an architectural space, even though air velocity is not increased. Finally, in model N3 (a real school building simulated), the performance of natural ventilation and the extracted chimney thermal convective effect is clearly observed, driving exhausting indoor air (hot and/or polluted air) towards the outside, at a greater air speed, not as large as in model N1 though, significant.

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Figure 7. Model N1. Cross ventilation using CFD to visualize and calculate air velocity and pressure

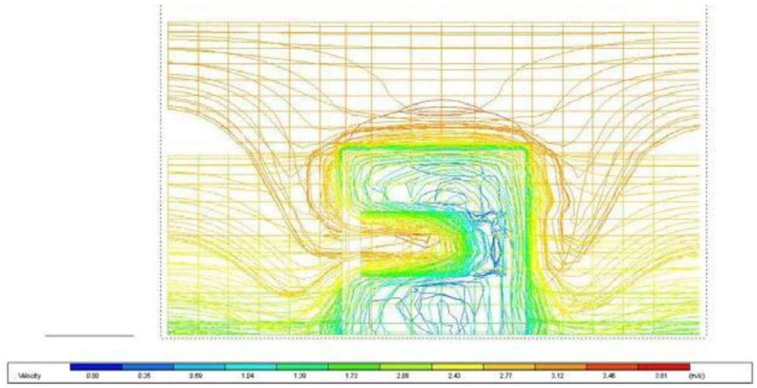


Figure 8. Model N2 Cross ventilation with Inlet (lower) and Oulet (upper) Openings. Ratio 1:2, using CFD to visualize and calculate air velocity and pressure

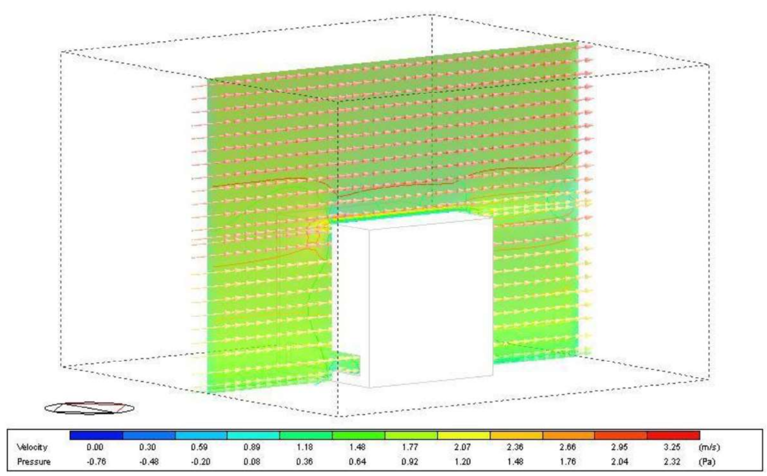
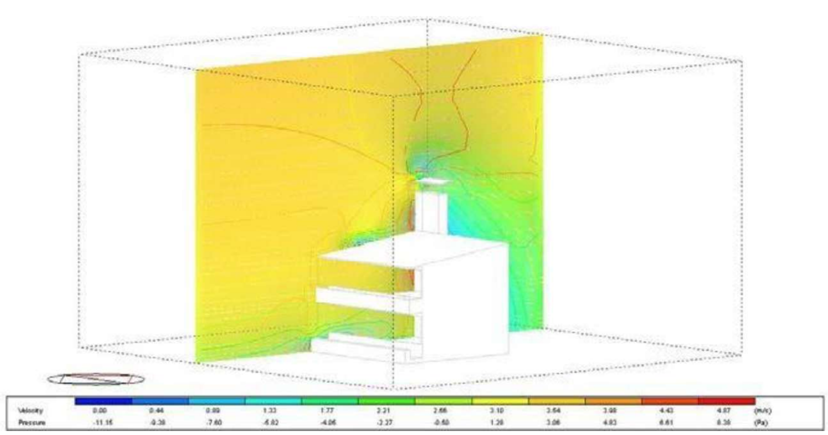


Figure 9. Model N3 Stack Effect. Educational Building with Wind Catcher and Chimney and Thermal Convective Effect using CFD to visualize and calculate air velocity and pressure



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7. ANALYSIS OF RESULTS AND INTERPRETATION

The experimental work demonstrated that the use of natural ventilation can provide hygrothermal comfort in real buildings. When comparing the cross ventilation design alternatives with wind direction perpendicular to the façade, that is at 90°, average percentages relative to the external wind velocities were reduced within a range from 15 to 21%. It was found that when wind direction was at 45º, the air movement inside the models was optimizes, increasing an average of 36% relative to the direct cross ventilation design alternative.

These results were consistent with previously reported studies (Kaiser, et al, 2015). As to natural ventilation simulations made through the use of CFD, this approach offers architects, designers and building practitioners, an essential tool for obtaining useful information of any architectural project about the behavior of air movement inside and outside the buildings, particularly since different strategies and systems can be analyzed and evaluated to optimize the design and performance of the project. Furthermore, the results can be oriented to achieve a bioclimatic and sustainable building which in turn can contribute to improve the ambient comfort conditions and health of the occupants as well as the environment and the quality of living.

8. CONCLUSIONS

The use of natural ventilation in buildings can contribute to accomplish health and hygrothermal comfort conditions for building occupants and this can eventually produce a significant reduction of energy consumption and energy savings, and consequently a decrease of the emission of greenhouse gasses to the atmosphere. This approach can also be useful to provide a true sustainable statement aimed at improving the natural environment and the quality of living for the present and future generations of all types of ecosystems, including the human beings.

This work demonstrated that by applying passive natural ventilation strategies in buildings, it is possible to achieve important economic, health and environmental benefits, particularly in buildings with high internal loads and in hot climates. The methodology of the experimental work conducted in this research can be particularly useful to provide sustainable educational design tools for schools of architecture, and engineering, as well as design alternatives for engineers and building practitioners, aimed to mitigate the climate change and the severe damage to the planet earth.

To sum up, further work in this extent is necessary and the new findings would certainly allow new opportunities to further extend the results obtained so far and to promote more research for other design conditions meant to contribute to the quality of living of buildings' occupants as well as to promote sustainability

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