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CITY, WIND, ENERGY: THE LIMITS FOR APPLYING NATURAL VENTILATION FOR ENERGY CONSERVATION TOWARDS THE URBAN DENSIFICATION IN HOT HUMID CLIMATE

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Abstract. It is widely known that urbanization can deeply compromise the city's atmosphere through the modification of the environmental parameters. Among the city's impacts over natural climate, great emphasis is placed on heat generation and changes on natural ventilation conditions that directly lead to thermal discomfort, compromising buildings energetic performance. Currently energy consumption is in the centre of the discussion about environmental preservation and sustainable development. Within the buildings it is emphasized the use of natural resources for building's conditioning. Specifically in cities with hot, humid weather, the case of Fortaleza, Ceará, Brazil (latitude 3° 43' S), natural ventilation is the main passive strategy to obtain thermal comfort. Therefore it is fundamentally necessary to understand the physical phenomenon and the aspects that influence natural ventilation process to objectively use the wind potential for cooling of buildings. On the other hand, it is becoming a major problem to maintain the potential to naturally ventilate the building's façades in urban centers because of the constructive densification and building's height, compromising the wind access to habitations. Based on existing standards air velocity should not exceed 0,2 m/s, otherwise it will compromise thermal comfort. However, latest researches about thermal comfort mechanisms in naturally ventilated buildings have shown that occupants of those buildings may prefer higher air velocities. The airflow around buildings creates a pressure distribution over buildings façades, an essential aspect to natural ventilation process. By creating high and low pressure zones over different parts of the building, the wind induces the air movement inside the building and once the city's spatial organization directly influences building's natural ventilation through the modification of pressure coefficients (Cp) over its surfaces, this research aims to determine the limits to urban densification in ways that it results in better conditions to the air movement in high-rise apartments. The study uses a Computational Fluid Dynamics (CFD) tool to analyze the airflow around buildings and inside the apartments, calculating velocity, pressure and flow. The objective is to adopt a set of urban and architectural solutions in order to dissipate the heat and improve indoor thermal conditions using natural ventilation, reducing the need for artificial conditioning.

1 INTRODUCTION

Urbanization process can deeply compromise the city’s atmosphere through the modification of the environmental parameters, generating heat island effects, thermal inversion, air pollution and changes over the wind and precipitation. Climate change caused by the city is actually documented in its regional and local repercussions. Among these effects, the excessive heat generation and changes in natural ventilation are highlighted because they lead to thermal discomfort and compromise the energetic performance of buildings.

Advances on the research about the aspects involved in the city´s dynamic development and its relation to climate is fundamental to understand the thermal response of the built environment, contributing to the local urban planning process, as attested by several studies (Chandler, 1976; Oke, 1987, 1988; Bitan, 1992; Katzschner, 1997; Assis, 2000; Duarte, 2000).

Higueras (2006) explains that the bioclimatic urbanism methods incorporate environmental and local constrains to define better suited urban planning guidelines once it considers the densification capacity in order to respect the impact over the environment in its relation to the natural site and the existing morphoclimatic domains.

Bioclimatic urbanism design experiences are far more developed in Europe. In Brazil, despite some attempts to link environmental parameters to the development of urban legislation as in Assis et al (2007), commonly the traditional and restrictive aspects adopted from other countries still remain. This restrictive attitude structurally compromises the progress of alternative proposals that consider environmental and energy demands, as attest Evans & Schiller (1996) and Mascaró (2001).

Currently, energy consumption is in the center of the discussion about environmental preservation and sustainable development. Despite the lack of a consensus about the concept of sustainability, it is possible to identify some necessary steps to achieve certain levels of development in balance with the environment. These steps involve the changing in energy consumption patterns, changes in urban legislation, some factual improvement in the waste and water treatment and in energy generation among other issues.

Within the buildings, the use of natural resources for conditioning is emphasized in order to reduce the energy consumption. The development of energy efficient buildings in their contexts is fundamentally necessary towards more sustainable environments.

Santamouris (2006) warns that as a result of intensive energy conservation measures, energy consumption for building heating has practically stabilized or even declined in recently years. On the contrary, the specific demand for cooling has increased dramatically mainly due to the fact that the family income has also increased and because air-conditioning systems became highly popular. On the other hand, as Kolokotronis et al (1996) attest, the monitoring of building’s energy consumption has shown that naturally ventilated buildings often spend less than 50% of the equivalent energy used by artificially conditioned buildings.

Natural ventilation, where is possible its application, provides fresh air to building’s occupants, contributing to the healthiness as it plays a crucial role supplying the oxygen and diluting the carbon dioxide. Also, it reinforces the cooling sensation through the acceleration of thermal exchanges between the individual and its surroundings (Frota & Schiffer, 2000; Yarke, 2005).

Especially in hot and humid climate regions, where there is a little variation in air temperature during the day and high levels of humidity, it becomes essential controlling solar radiation and increasing the air movement within the urban fabric and inside the buildings.

According to existing standards (ASHRAE, 1992; ISO, 1994) indoor air velocity should not exceed 0,2 m/s. Beyond this limit there is a risk of compromising thermal comfort. However, latest research on the mechanisms of thermal comfort in naturally ventilated buildings showed that the occupants of these environments may prefer higher air velocities (Nicol, 2003).

Based on the research of Brager & Dear (1998), ASHRAE 55 (2004) proposed an adaptive model and a specific method for using it in naturally ventilated buildings situated in regions with average monthly temperatures between 10 °C and 33.5 °C. The method, which considers the absence of artificial air conditioning system and physical activity with low metabolic rates (between 1.0 met and 1.3 met), is applicable to environments in which the building occupant can control spatial options in order to adapt himself to the climatic variations (e.g. opening windows and changing clothes).

Meanwhile, the use of the wind potential for passive cooling of buildings makes necessary to understand the physical phenomenon and the factors that influence the natural ventilation process (variable factors such as local wind characteristics, the built environment in the surroundings and internal factors such as openings sizes, locations and characteristics).

As the wind passes through the building, it creates a pressure distribution around its facades. This pressure distribution is essential to natural ventilation process once it creates zones of high and low pressures on different sides of the building that induces the air movement inside the building. Therefore, this flow is essentially dependent on the pressure coefficient on the building’s facades.

Pressure coefficient (Cp) is an empirical and dimensionless parameter that characterizes the airflow. It represents the pressure changes induced by the air movement and which are caused by the influence of the surroundings characteristics on local wind behavior (Liddament, 1986; Allard, 1998). Accordingly, Cp values are modified according to local topography and roughness of the terrain.

Commonly, Cp values are obtained through algorithms based on wind tunnel researches on low porosity solid models. However, Cóstola and Alucci (2009) explain that obtaining Cp data according to this method is not always possible, due to high costs of these experiments, equipment and expertise involved.

Cóstola; Blocken; Hensen (2009) attest that when determining pressure coefficient values through the wind tunnel technique is not achievable, it is possible to define it using computational fluid dynamics softwares, widely known as cfd tools. In its conclusions, Cóstola & Alucci (2009) ensure that with appropriate conditions and parameterization of the mesh, the adoption of an appropriate turbulence model and the systematization of the steps of the simulation, it is possible to determine reliable values of Cp for thermal comfort studies.

The objective in wind and thermal comfort studies consist in crossing the results generated by the programs with the site’s architectural and environmental characterization, developing guidelines to minimize negative impacts of urbanization on natural ventilation.

Simulating the wind through CFD applications is a valuable tool in the analysis of climate suitability for built environments. The method was tested in the assessment of urban natural ventilation conditions in various works, identifying the influence of different urban forms as the result of the land occupation permitted by urban legislation on the airflow.

Although natural ventilation within the urban space theme has been studied in several researches, the interference of the urban form over indoor air movement remains largely unexplored (Cheung & Liu, 2011). Thus, using a cfd tool, the study aims to reveal how different urban density morphologies modify the wind pressure field on high-rise residential buildings, which might compromise the performance of natural ventilation inside buildings.

This work is a technical note and intends to present the first steps and the methodology adopted to carry out this research about urban densification and its effects on indoor natural ventilation assessment.

Once the obstacles in the neighborhood significantly affect Cp values and also considering that the study about urban densification and environmental conditions still need some answers, it becomes crucial to understand the limits and possibilities of the city growth in its relation to the need of natural ventilation inside the buildings.

Freitas (2008) explains that the proper urban density for a specific area is a relative term. Higher or lower densities can endanger the natural environment and the life quality, compromising environmental sustainability.

The choice for the city of Fortaleza is due to the fact that the city´s current configuration has various environmental problems due to the change of its natural components, compromising the quality of life of city´s inhabitants. Also, the recent and rapid urban growth is characterized by some specific actions, not considering an overview of environmental issues as major guidelines to urban planning.

The modification of Fortaleza´s natural climate is a documented fact, highlighting the 50% decrease in the rate of wind speed, as attested by Xavier (1996; 2001). This specific aspect is sufficient to induce new urban plans in acquiescence to urban climate attributes once natural ventilation is the main passive strategy for thermal comfort to the city, located at 3° 43 ´S. Therefore, it becomes crucial to incorporate it into constructive proposals guidelines and urban legislation.

Cândido & Bittencourt (2005) emphasize that for a proper using of natural ventilation as a thermal comfort strategy in buildings, the frequency and intensity of the local wind should be consider, analyzing low wind speed periods. The existence of this kind of periods, especially in warmer seasons and during daytime, prevents the adoption of this strategy.

However, the analysis and systematization of wind data period between 2002 and 2009 for the city of Fortaleza presented in Leite (2010) indicates a high potential for applying natural ventilation as a thermal comfort strategy due its relatively constant frequency and intensity as shown by wind-rose plotted (figure 1).

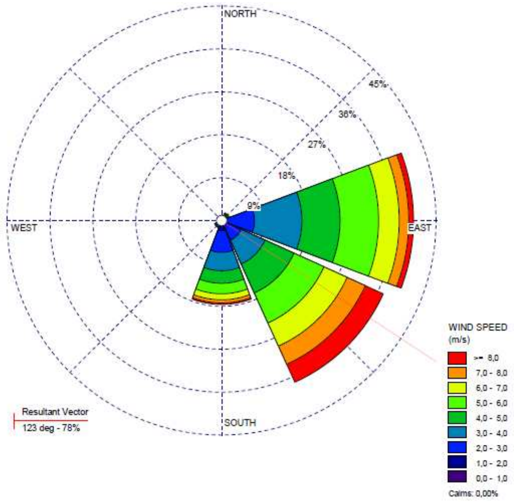

Figure 1 – Wind-rose plotted for the city of Fortaleza after analyzing the period between 2002 and 2009.

In addition, higher air velocities are more frequent during the afternoon, period which air temperature is higher and, consequently, higher ventilation rates are more necessary to reach thermal comfort zone, as shown by figure 2.

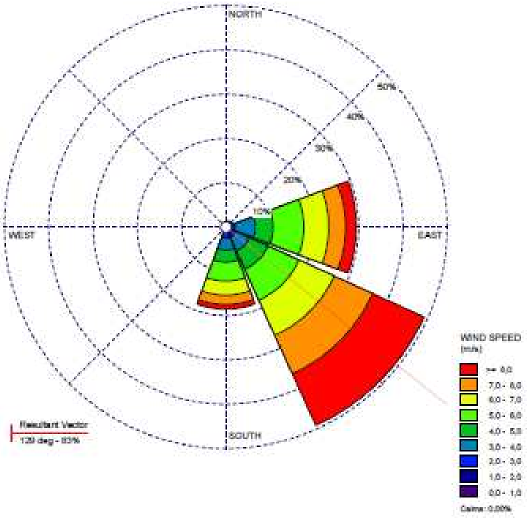

Figure 2 – Wind-rose plotted isolating the afternoon period between 2002 and 2009.

1.1 Research objective

This is an exploratory research in its initial steps and presenting itself as a development of the theme investigated during the author´s master degree. Yet, new levels of complexity are now desired and targeted by adding the assessment of natural ventilation inside the buildings to the analysis of the wind disturbance due to the urban fabric in its process of densification.

The main objective is to evaluate the influence of different urban built arrangements over indoor natural ventilation conditions, analyzing residential apartments units through a numerical correlation between the pressure field due to wind on external facades and the various urban density scenarios allowed by local legislation.

1.2 Hypothesis formulation

Assuming that the pressure over the building envelope can be used to express a parameter that indicates the potential for an opening to inflate (pressure positive) or extract (negative pressure) air and generate an air movement inside the building and also that urban constructive arrangements have direct influence on natural ventilation of buildings, it is possible to control and/or stimulate the urban form by determining the limits for constructive densification so that this will result in improved internal airflow to buildings.

2 METHODOLGY ADOPTED

As a first part of this research a comprehensive e extensive study about natural ventilation phenomenon and the limits of its application for thermal comfort for building’s occupants in hot and humid climate has been performed in part and will be continued. In addition, a detailed review about the adaptive comfort index and its application for naturally ventilated buildings should be performed.

Then, a few steps should be taken in order to prepare computer simulation tools to analyze the airflow within the urban fabric and inside buildings. First, choosing a better suited turbulence model for the specific cfd tool used in this research (between k-ε model, Detached eddy simulation and Large eddy simulation).

Subsequently, the proper scale of the structured or unstructured three-dimensional mesh should be calculated in order to perform precise measurements of pressure coefficients, airflow inside buildings and air changes rates according to windows size and characteristics.

Also, the adoption of logarithmic profiles corresponding to typical urban roughness (Z_0) should be taken from Prata-Shimomura (2010). The tests perform by the author’s investigation represent a recent approach in roughness research over urban areas using wind tunnel and cfd analysis to define better suited values for urban densification in parts of São Paulo, in Brazil. The methodology aspects used in this investigation and can be applied to define proper Z_0 values for the city of Fortaleza, once there are parts of the city fabric with similar morphologic characteristics between these two cities.

As a second step a study area within the city of Fortaleza will be chosen. This part of the city should represent a densely built urban track with a high aerodynamic roughness (Z_0) as a way to perform a test and validation of this research as close to extremely urbanized areas as possible. However, for computer modeling purposes only a stretch of 3 x 3 blocks within this area will be modeled, as an example shown by figure 3. This representative urban area will be used as a pilot for implementation of the study, analyzing the primary results and to validate the models. The understanding of the airflow patterns within this part of the city is a secondary objective, justified as a necessary physical object to develop an empirical study.

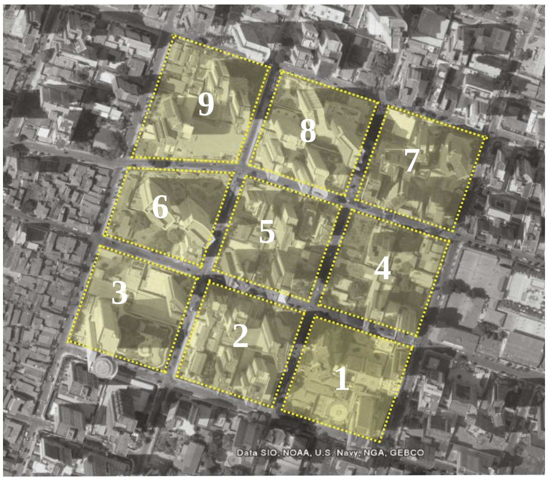

Figure 3 – Densely built part of the city of Fortaleza that will be used as study area

This representative urban area will be modeled in a Computer Aided Design (CAD) software. Then, a several possible scenarios will be created as simplified three-dimensional models representing different urban densification arrangement possibilities in replacement of the existing buildings. These scenarios will be then submitted to the CFD application to simulate the airflow within the urban fabric.

For Cps and airflow rates calculation, modeling will indicate the points of interest that should be located in the center of the openings on main building´s façade. The analyzed building is located in a center block which is surrounded by eight neighboring blocks that will settle the various urban scenarios created as possible variations for the other buildings in accordance to the existing urban standards (e.g. maximum height, clearances), as highlighted in red color on figure 4.

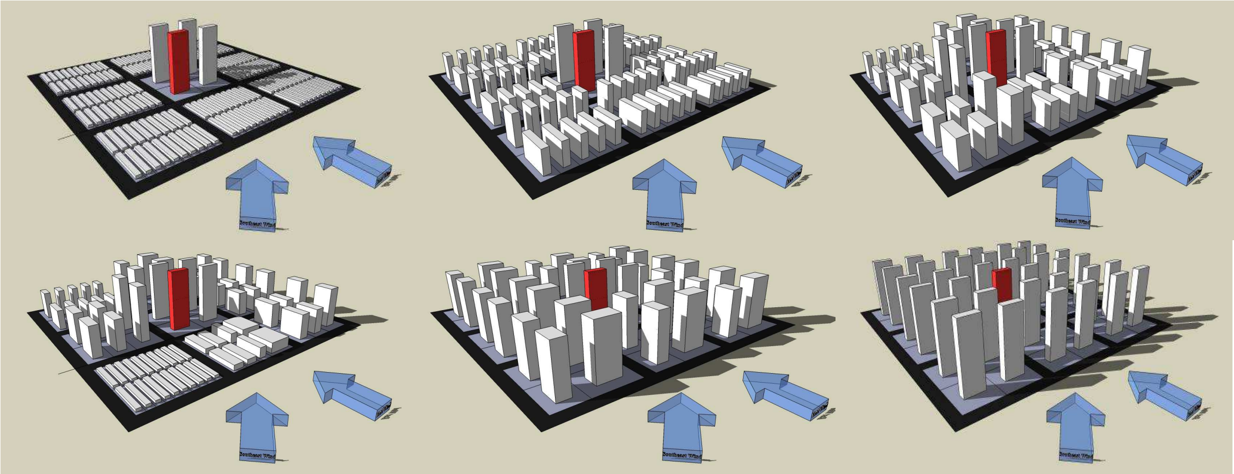

Figure 4 – Some examples of urban design possibilities generating the multiple scenarios that will be simulated in the cfd tool ambient to visualize the airflow within the urban fabric and then calculate different Cps in accordance to various roughness levels.

In the simulations of each urban scenario only the east and southeast wind directions will be applied as initial and boundary conditions in the cfd tool. This choice is due to the wind data analysis performed in Leite (2010). The information about wind regimes in urban areas can be implemented from the survey analysis and organization of existing information in exposed locations.

For the study of natural ventilation in the urban environment and its effects on indoor air movement ANSYS-CFX (ANSYS, 2005) software will be used. This cfd tool was applied in previous researches and the experience in using it in the investigations carried out by the Laboratory of Environmental Comfort and Energy Efficiency of the Department of Technology in the School of Architecture and Urbanism, University of São Paulo.

The CFX is an example of cfd produced by the ANSYS Company that allows the simulation of any situation involving fluid mechanics in any scale and boundary conditions, as long as the computational capacity is provided.

The software consists of 4 modules. In the pre-processing level the geometry is prepared in CAD ambient by determining the area of the model to be adapted in ANSYS ICEM CFD for the development and parameterization of the mesh, defining the points where the equations should be calculated. For the model construction, the buildings are simplified, which reduces considerably the processing time and computational capacity for calculating the simulation. Then, the definition of the system simulation, equations to be calculated, the initial and boundary conditions and the turbulence model are adopted in CFX-Pre.

The simulation is then calculated in the CFX-Solver and the results are viewed through three-dimensional images and graphics in CFX-Post, inserting points, lines and planes in various locations, allowing the visualization of the airflow in different parts of the model through velocity contours, vectors or streamlines.

For the study of natural ventilation patterns through openings the applied mesh in each scenario will include windows only in previosly selected heights, simulating the airflow inside the apartment in the building's basis, at its middle and on the top of the main building, as shown by figure 5. Such simplification is necessary due to the computational capacity availability, limitating the amount of openings to be analyzed in the airflow rate and pressure field according to each scenario created.

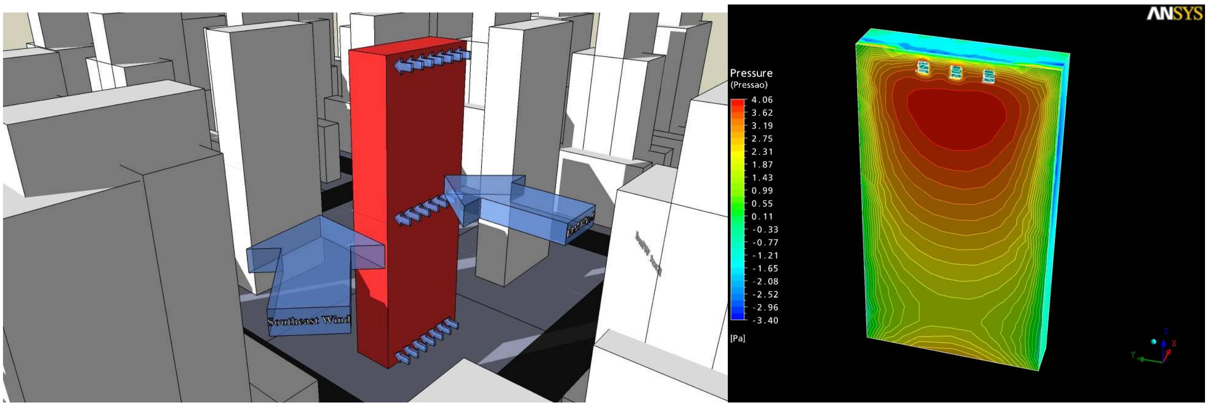

Figure 5 – Defition of the points of interest on the openings at the basis, middle and top of the main building's front façade in which the pressure coefficient and airflow rates should be calculated.

3 ANALYZING THE EXPECTED RESULTS

The airflow rates inside the apartments will be calculated using the pressure coefficients (Cps) generated on the main building´s facades as a result of the wind simulations for each urban density scenario designed.

After each simulation, in post-processing module (CFX-Post), the calculated air pressure data over the points located in the center of the openings in the front and rear facades of the main building will be exported to a spreadsheet. One additional point should be positioned in undisturbed flow for the measurement of air speed and air density and applied to the dynamic pressure calculation.

With these pressure values, the calculation of the Cp at the specified points of interest will be performed using equation 1 below.

$$Cp = \frac{2 . q_{real}}{v^2 . \rho} \tag{1}$$

Where: Cp = pressure coefficient
q real = dynamic pressure (Pa)
v = air velocity (m/s)
ρ = air density (Kg/m³)

The airflow rates inside the main building is then calculated using equation 2, which takes the size and discharge characteristics of each of the openings involved in the simulation.

$$Q = \left[\frac{(Cp_1 - Cp_{n+1})}{\frac{1}{Cd_1^2 A_1^2} + \frac{1}{Cd_2^2 A_2^2} + \ldots + \frac{1}{Cd_n^2 A_n^2}} \right]^{0,5} \tag{2}$$

Where: Q = taxa de fluxo do ar
Cp_1 = Pressure coefficient on inlet opening
Cp_{n+1} = Pressure coefficient on outlet opening
V_z = air speed on the opening height (m/s)

Cd_1 = Discharge coefficient of the opening
A_1 = Inlet opening aera (m²) x cosine the wind incidence angle
Cd_2 = Discharge coefficient for internal openings
A_2 = Internal opening area (m²)
Cd_n = Discharge coefficient for outlet
A_n = Outlet opening area (m²)

Based on the simulation results and airflow rates inside the building an electronic matrix will be elaborate in order to relate the numerical field of pressure coefficients on the main building´s facades in each scenario and its effects on airflow indoor, changes on air speed and the necessary flow to maintain acceptable operating temperature values define by the adaptive temperature chart, as shown by figure 6.

The adaptive model was adopted due to its appliance to naturally ventilated buildings once no limits of air velocity are imposed. In the proposed model acceptable operating temperature ranges are defined specifically to the environment and the model relationship to internal ventilation is given by the coefficient of convection heat transfer, known as hc in the equation 3 below. The mean radiant temperature (TRM) should be calculated for the hypothetical flat inside the main building in the simulations. The dry bulb temperature (TS) is taken from the weather data for Fortaleza and the radiant thermal exchange coefficient is considered as a fixed value for indoor simulations.

$$To = \frac{(hr \times TRM) + (hc \times TBS)}{(hr + hc)} \qquad (3)$$

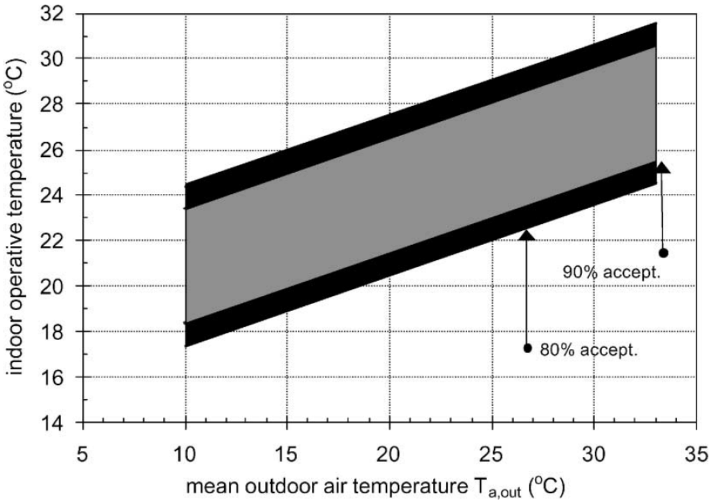

Figure 6 – Acceptable temperature ranges in naturally ventilated buildings according to average monthly temperature and dissatisfied percentage.
Font: ASHRAE 55 (2004).

4 ACKNOLEGMENTS

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