

THE INFLUENCE OF CEILING HEIGHT IN THERMAL COMFORT OF BUILDINGS: A CASE STUDY IN BELO HORIZONTE, BRAZIL

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ABSTRACT

Buildings are created to provide adequate climate conditions for the activities performed by occupants. According to thermodynamics and heat transfer principles, the thermal inertia of indoor environments is directly proportional to the volume of that environment. Based on these principles codes of practice for thermal behaviour of buildings have been established in different countries allowing to reduce ceiling heights while influencing indoor air temperature and reducing the indoor environment thermal inertia. For hot weather locations, such as in tropical countries, during most of the year, the reduction of ceiling heights causes a small increase in indoor temperature of environments. In addition, studies both in laboratory and based on mathematical models show that the variation in temperature between the upper and lower layers of an internal environment can reach up to 4 °C. Another consideration to be observed is that internal environments must have openings for ventilation, a mechanism that helps to control air temperature and the human sensation of heat. Taking as example the Belo Horizonte Building Code, a town in southeast of Brazil, in Minas Gerais State, between 1940 and 2010, when the usual minimum ceiling height reduced 40 cm, there were no compensatory changes in the Building Code of Practice related to the ventilation openings or other heat-control mechanism. In the last decade, other standards and technical manuals on the subject emerged, with certification systems and energy efficiency rating similar to the Green Building, such those existing in several countries. Aiming to evaluate the ceiling height influence on the environments' internal temperature, for this study three full-scale models, of 8 m²

room area, and window area of the 1/6 floor area, according to the minimum standards established by the Belo Horizonte Building Code of Practice were constructed. They were built in of ceramic blocks structural masonry, varying the ceiling height in the range of 3.00 m, 2.80 m and 2.60 m allowed by technical regulations since 1940 up today. In each one, thermocouples were installed at different heights for monitoring the internal temperature without ventilation, collecting data from winter to summer. Preliminary results indicates that temperature increases of 1°C for each 20cm reduction As the temperature range of human comfort is small, these variations, however subtle, may cause thermal discomfort to users.

Key words: ceiling height, building code of practice, thermal comfort.

Introduction

To understand the issues related to thermal comfort in buildings is also necessary to know the materials properties and buildings components related to the processes of heat transfer. The knowledge of these properties is essential to the development of building designs following the principles of natural thermal conditioning and evaluations of thermal buildings behavior (FERREIRA, 2003).

In the 1960s, the Olgyay brothers applied bioclimatology in the architecture considering the human thermal comfort and creating the term bioclimatic design that sought favorable climate conditions in order to satisfy the human thermal comfort. They also developed a bioclimatic diagram that proposes strategies for adapting the architecture to the climate. Later, the Israeli architect Baruch Givoni, in 1969, developed a bioclimatic chart for buildings which corrected some limitations of the Olgyay's diagram, based on principles of psychometrics (LAMBERTS, DUTRA and PEREIRA, 1997).

A building absorbs thermal energy from the external environment through the mechanisms of radiation and convection. The intensity of this heat flow will depend, among other factors, of wall thickness, heat capacity of the material, density and thermal conductivity. In addition, there will always be a pair of psychometric and relative humidity at each time inside the building that may or not be comfortable for a person. Through the phenomenon of convection, the fluids have a natural movement in which hot masses, with lower densities than cold masses, tend to rise. Therefore, the temperatures in the higher levels tend to be higher within the environments. Depending on the volume of hot air and the size of the openings, hot air layers tend to be formed in the upper regions (Figure 1). Thus, as higher the ceiling height, more distant the hot air layers will be of the users.

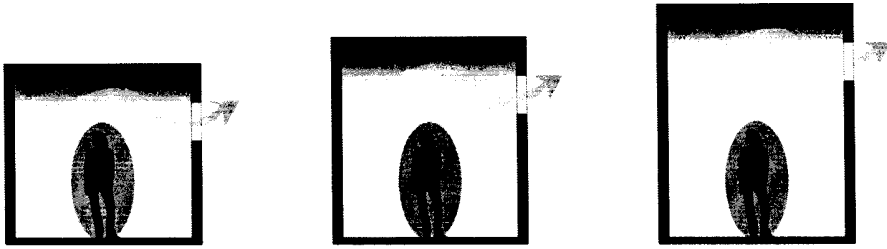


Figure 1. Position of hot air layers in the environments in the upper region.

The thermal conductivity is one of the main variables involved in designing and in the climatic optimization (AKIYOSHI, SILVA et al., 2001). The determination of the rate of heating and cooling are fundamental for understanding the resulting temperatures. This may be considered for any material that makes up a building and performs heat exchanges.

Based on this phenomenon, there are several manuals in the world with directives and recommendations, but they are not mandatory. Instead, standards should be followed, although many municipal governments in Brazil do not require to be complied when the projects are approved. Two examples of standards that address more systematically the materials and climate are the NBR 15.220: Thermal behaviour of buildings (ABNT, 2005); and NBR 15.575: Buildings housings up to five floors – behaviour (ABNT, 2008). About the manuals, Brazil has, for example, the Technical Regulation on Quality – TRQ to the level of Energy Efficiency of Residential Buildings (MINISTÉRIO DO DESENVOLVIMENTO, INDÚSTRIA E COMÉRCIO EXTERIOR, 2010). It classifies the buildings according to the level of the highest energy efficiency (class “A”) to lowest (class “E”).

Initially developed in the 1970's, computer tools for the simulation of the behaviour of buildings for the comfort analysis has increased in the 1990's, with the popularization of personal computers, companies and research groups that developed programs based on compatibles languages with the operational systems (MENDES, WESTPHAL et al., 2005). Although the capacity of the computers has been progressive advances and more complex softwares have been developed in several countries, phenomena such as heat flow and air flow are complex and computational tools are typically used only in research centers at universities and institutes, with low or any relation to the vast majority of engineering and architecture offices.

The building projects, however, are not the result of demands resolved only technically. They are also subjected to other variables such as the buildings market and local regulation. In Belo Horizonte, legislation and practices of the buildings market show that these variables many times override the techniques.

Thermal Behaviour of Internal Environments

According to empirical observations and considering the physics laws, the ceiling height has a direct influence on the internal environment temperature, since in higher environments the air volume is greater. In addition, the openings size for ventilation and their heights from the floor are also important in internal temperature. As larger and higher, more air flow pass between the internal and the external environment. In tropical countries, such as Brazil, this may occur if, for example, there is great air flow that allows ventilation with removal of heat, or through higher ceiling heights, which will cause the hot air layers to remain away from the users.

Over the years, the Building Code of Practice in Belo Horizonte has changed allowing lower ceiling heights, due to cost factors that benefit the buildings market. The reduction of the height of each building floor represents reductions in the quantities of masonry, structural loads, columns height, pipes, coatings, use of workmanship and affecting the capital investment return. However, in hot weathers, in most months of the year, the reduction in the ceiling height tends to cause temperatures above the comfort ones. In addition, the legal parameters related to environmental comfort do not address the thermal phenomena systematically, leaving out several physical variables involved, such as wind speed and their dynamic effects, vegetation shading and surrounding buildings, thermal conductivity of materials among others.

Most mathematical models used to quantify the heat stored by a given building element that depends of several factors use only the product of mass by the specific heat, i.e., its heat capacity. However, this process generates inaccuracies, as the stored energy is less than that calculated in this way, since, the mass located closer to the surface in contact with the air inside has a greater participation in the heat transfer and suffers greater fluctuations in temperature and being, thus, a more efficient storage (ALMEIDA, GARCI et al., 1997).

Several studies have been conducted in many countries about environment thermal behavior, either through monitoring buildings as with computer tools and CFD – Computational Fluid Dynamics –, generating more detailed results. For example, Hashimoto and Yoneda (2009) compared different ceiling heights and their influences with ventilation and thermal load. The results showed that the higher environments have temperatures closer to comfort ones. Besides this, the results of Zhai and Chen (2004), Lam and Chan (2000), and Katsiris Stamou (2005) and Zou, Opara and McKibbin (2005) in their respective researches on thermal environments analysis through software CFD showed temperatures stratifications according the levels in a direct proportion with the distance to the floor. However, although several conclusions may be applied to other cases, the results of each one represent a specific context.

Several researches projects conducted on full-scale models have also been performed. For example, in 2006, Huang Zhijun et al. (2007) installed 221 temperature sensors at various points of the Shanghai International Gymnastics Stadium during a summer day, a winter day and one day in a transitional season. In another study, Krüger and Givoni (2007) followed the thermal behavior throughout the year for a single-family residential home located in Headquarters Boqer in the Negev desert in Israel. In both, the authors found a relationship between the internal and external temperatures which relates to other variables such the climate and building materials.

This research presents the study of variation of the minimum permitted ceiling height by the Belo Horizonte Building Code of Practice over the years with the thermal behavior of the internal environment. The objective is to compare the thermal behavior of the internal environment with ceiling established in three different moments by this code. For conduct the study, three full-scale models were built with structural ceramic masonry. The use of these materials is due the reason of constituting buildings systems rationalized and submitted to more rigorous controls than the masonry for fence, which provides more accurate results. Also, traditionally in Brazil, the masonry is a largely used building material and the structural type is typically used in this construction system with better quality control that, for this and other reasons like costs and simple techniques, has been increasing market share in Belo Horizonte, especially for repetitive building production. It is known that many studies have been developed to improve this system that, compared to the traditional construction method with concrete structures and partition masonry, provides costs reduction and better quality construction.

Evolution of the parameter “minimum ceiling height” in the Belo Horizonte Building Code of Practice

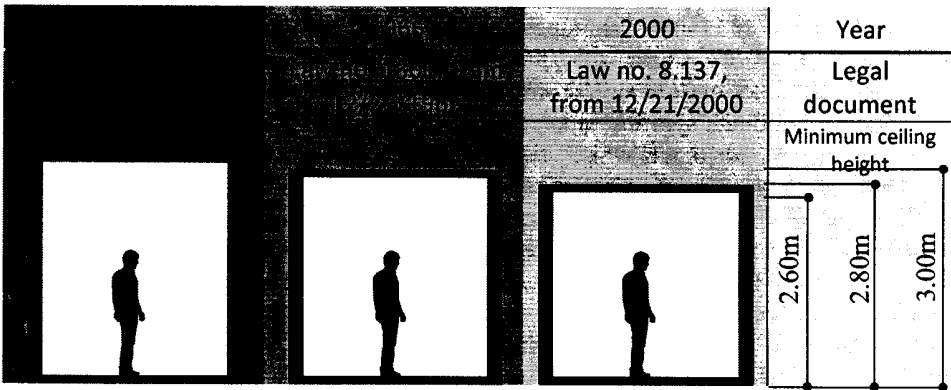
When visiting the older residential buildings in Brazil, especially those built in the beginning of the twentieth century, it is observed that their ceiling heights are higher than today. In 1950s, the minimum ceiling heights in Brazil were among the highest in the world for environments of prolonged stay in residences. The parameter ranged from 2.70 m to 3.00 m, as well as Chile and Egypt. However, at the same period, countries like the United States, Canada, England, South Africa and New Zealand allowed ceiling heights between 2.10 m and 2.40 m. But for some regions of Japan and Syria this parameter was higher, being 3.30 m and 3.90 m respectively (STINSON and BRASS, 1960).

The law that determines the minimum ceiling height in the municipalities is the Building Code of Practice. In Belo Horizonte, this code, originally Decree-Law no. 84 of 12/21/1940 (BELO HORIZONTE, 1940), suffered some specific and sporadic alterations over the years, but kept original concept from 1940. This Code of Practice is still valid, although with some articles reviewed, updated and deleted until 2010,

the year that the Decree 13842 of 01/11/2010 regulates Law no. 9725 of 07/15/2009, which updated this Law (BELO HORIZONTE, 2010).

According to the Belo Horizonte Building Code of Practice, from 1940 until 2010, the minimum floor area of the dormitories remained unchanged, as well as their minor areas of lighting and ventilation openings. However, minimum ceiling height, which was 3.00 m since 1940, declined in 1966 to 2.80 m and to 2.60 m in 2000. Table 1 summarizes and illustrates this regulation temporal evolution.

Table 1. Minimum heights of environments from 1940 to 2011 according to the Belo Horizonte Building Code of Practice



Comparing the buildings after the second half of the twentieth century with its predecessors, it is observed that the new parameters approached those used in other countries in the 1950's. However, the decrease of the ceiling is not a peculiarity of Belo Horizonte. In other Brazilian capital cities, independently of the different climates in which they are, the decrease also occurred, and today they have similar legal parameters. As examples, according to their Building Codes of Practice, considering the same type of place, the minimum ceiling height is 2.60 also in Florianópolis and Salvador. On some others, this parameter is 2.50 m, as in São Paulo, Campo Grande, and Maceió. These cities are much distanced from each other and are located in different climates. As showed, in that case, the local climates are not the factor to determinate the minimum ceiling height.

Models Construction

Conceptually, the models consisted of housing dormitories units dimensioned with the limiting parameters of floor area, window area, ceiling height and window-ceiling distance (minimum or maximum) of the three moments of the Belo Horizonte Building Code of Practice. The models were designated as “A”, “B” and “C”. All the walls were built with ceramic blocks of 14x19x29 cm. As for others construction

materials, the three models were similar, each one containing: reinforced concrete floor; flat ceiling of reinforced concrete with 8 cm thickness; 01 windows glass consisting of a fixed flat and colorless glass 4 mm thickness on the dimensions 1.06 x 1.40 m; a steel door on the dimensions 0.70 x 2.10 m.

To use the structural masonry system's potential, the walls were built with dimensions that agrees with dimensions of the blocks, meaning that each dimensions of the room is a multiplying factor of the block dimension. Thus, the resulting internal environment has 2.40 m wide and 3.45 m long internal, which represents a free floor area of 8.28 m². Figure 2 illustrates the dimensions of the model "C", which apply to the other ones, except for the ceiling height and window position.

As from 1940 to 2010, about the parameters described above, there were only changes in the ceiling height for this type of environment, only this parameter is changed in the three models – and thus the sill height and the ceiling distance of the windows. All of them have the same plant type and similar transverse section (Figure 2).

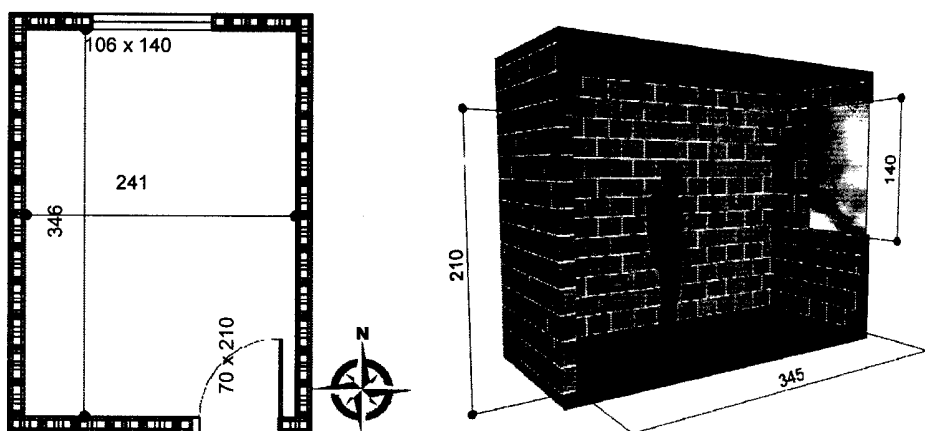


Figure 2. General plant of the models and transverse section of model "C" (distances in centimeters).

Since the models were built in full scale, they are considered as true models, in which all the significant features of the prototype are faithfully reproduced to scale (MURPHY, 1950). Thus, it was not necessary to make dimensional analysis calculations.

Due to the latitude of almost 20 OS, during the summer, the north-oriented facades receive little sunlight during the day. Thus, all the three models were positioned to have the facades with windows oriented to the north, making the heat from the radiation less intense. As the dimensions of the window are not multiple of 5, it was

the result of an adjustment between minimum area of lighting and ventilation as well as the building codes, the dimensions of the blocks of masonry, and also height and window-ceiling distance. The site available for the implantation of the models is a wide space without shading in the factory field. Moreover, to avoid that any model projected shadows in the other one in any time or day of the year; they were distanced from 11.40 m of each other. This distance was obtained from a previous insulation study.

In relation to the finishes, all materials were used without coverings to avoid others layers and different thermal resistances, which would make the study more complex. As the study period covered the rainy season, a waterproof was made with a PVC geomembrane with geotextile. The three models were built in accordance with the dimensions summarized in Table 2.

Table 2. Summary of dimensions of the models and limiting parameters of the Belo Horizonte Building Code of Practice

Parameter	Model "A"	Model "B"	Model "C"	
			Model	Limit in 2010
Width (m)	2.40	2.00	2.40	2.00
Length (m)	3.45	3.00	3.45	-
Ceiling height (m)	2.80	2.80	2.60	2.60
Floor area (m ²)	8.28	6.00	8.28	8.00
Window area (m ²)	1.43	1.33	1.48	1.33
Window-ceiling distance (m)	0.40	0.47*	0.20	0.43*

* Maximum window-ceiling distance permitted. The others parameters refer to the minimum.

Data Collection

To collect all data from internal and external temperatures, it was used the method used by GOMES (2010) to study thermal comfort in schools, which consists of positioning temperature sensors in the environment and monitoring them for a specific period. In the present study, thermocouples type "J" were installed with 30 cm shaft length in each of the models and in the external environment following data being: (I) internal dry bulb temperature - DBTINT; (II) internal wet bulb temperature - WBTINT (III) external dry bulb temperature – DBTEXT; and (IV) external wet bulb temperature – WBTEXT.

For fixing the thermocouples in internal environments, it was fixed at the center of each ceiling a vertical shaft of light wood, at 1.20 m from the floor, where the WBTINT thermocouple was fixed. To this point, it was made a device which consists to involve thermocouple shaft with a cotton cord connected to a water recipient. Thus,

the thermocouple will be always wet. The three DBTINT thermocouples were set to stay in a horizontal position, from a ceiling distance of 20 cm, 40 cm and 60 cm. These distances, called "Y1", "Y2" and "Y3", were kept in the three models, as exemplified in Figure 2. About the external data, it was fixed a wooden rod into the soil with 1.20 m high, where the thermocouples were fixed. All internal and external thermocouples were connected to cables that, within underground conduits, conducted the signs to an analog receiver module which transmitted the data to a computer located in the factory building, in a weather protected place next to the models.

All data are stored in the computer and saved in spreadsheets. From this, it will be possible to make statistical calculations and comparisons between the thermal behaviors of the models through graphics. The data collection system started on December, and since this date, it collects and stores the temperatures of thermocouples every five minutes, 24 hours a day. Thus, this study still presents preliminary results.

Preliminary Results and Conclusions

The preliminary results points to a warming according to the increased level in all the models, due to the density difference between hot and cold air masses. The temperature difference between the 1.20 m level and the limit of the ceiling height varies around 0.7 °C.

In addition, the 20 cm ceiling height reduction indicates an increase in temperature at points "Y1", "Y2" and "Y3". Although this variation is lower than 1 °C, it was expected, since the reduction of the ceiling height decreases the volume of internal air and, consequently, the thermal inertia of the environment. Although the model with a higher ceiling height also has more areas exposed to heat, the ceramic blocks have low thermal conductivity coefficients, and the difference of the heat entrances among the three models is low.

Based on the physical properties of fluids, that the warmer masses with lower density tend to rise, it's possible to say that the higher temperatures at points "Y1", "Y2" and "Y3" for model "C" is an expected result.

Another important observation is about the temperature differences among the models. Although less than 1 °C, they were perceptible to the tact, which indicates that are significantly important for thermal comfort. At the end of data collection, it is expected that the results of WBTINT temperatures may clarify this empirical observation, since the thermal comfort is directly related to psychometrics. At last, it is also important for understanding the internal environments behavior and their differences relation to the DBTEXT and WBTEXT analysis, since all thermocouples data of the research are simultaneously collected.

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