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Rapid on-site evaluation of thermal comfort through heat capacity in buildings

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Abstract

A simple, straightforward procedure to estimate the effective thermal mass of a building is established. Basic measurements of inside and outside temperatures are shown to exhibit several common characteristics, so that a single value for the effective thermal inertia can be derived. A relationship between the delay in the internal temperature to attain a maximum value with respect to the ambient, and the temperature amplitude attenuation inside the building, is found to exist, and its dependence on maximum outside temperature is explored. This procedure is shown to be useful to rapidly classify buildings or dwellings according to the effectiveness of the participation of its thermal mass in damping extreme temperatures, such as those found in regions with dry climates. The procedure hereby proposed has also been useful to estimate the relevance of thermal mass of a given building in power savings in HVAC.

Keywords: Thermal inertia; Comfort; Passive; Energy savings

1. Introduction

The relationship between thermal comfort and heat capacity in dwellings and other buildings has been appreciated since man has built his own house. In a climate where temperature variations with time (daily or seasonally) are important, the management of heat storage has been always an issue. This is true both when ambient temperatures drop below comfort limits at night and when temperature rises above that limit during the day. In a changing climate, such as is characteristic of heavily populated dry climate regions of the earth, the proper management of the thermal capacity can influence very drastically the power requirements for heating and air conditioning, regardless of the proper use of the other passive options for energy savings.

A recent study by [1] includes a very extensive research of literature relevant to this topic. A guideline is thus identified and energy savings are calculated for various thermal capacity strategies in houses [2]. This concept has resulted in a rich variety of research into massive building techniques such as a rock shelter [3] and earth integrated rooms [4,5]. The idea of managing the thermal capacity to increase comfort and reduce power requirements in the desert has occupied several researchers [6–9]. It is found that several methods can be applied to combine the traditional or vernacular architectural styles and building capacities with modern requirements of urban developments, in order to secure comfort with passive techniques [10]. The approach to thermal comfort by increasing thermal capacity in the building materials has also proved viable in southern Europe [3,11], Malaysia [12], the Philippines [13], and in general tropical climate [13–15]. The authors of this paper have also proposed a method to evaluate the importance of passive techniques in the hot and arid northwestern parts of Mexico [16]. Other authors (i.e., [17]) have applied the same basic first law of thermodynamics, as well as energy and exergy analyses, to calculate the savings both in cooling and heating with the aid of added thermal mass.

However, the basic physics of employing a certain thermal mass to aid the air conditioning process is very complex and cannot be addressed directly. Any house or building is the

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Nomenclature

A	area (m^2)
C_p	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
K_t	$= UA/MC_p$, (s^{-1}), total conductance divided by the thermal capacity
M	mass (kg)
Q	heat flow (kJ)
T	temperature (°C or K)
t	time (s)
U	global heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)

Subscripts

a	ambient
i	interior
j	any heat transfer process of the nth set
n	number of heat transfer processes that occur simultaneously
t	time

theater of a very rich and complex array of thermal flows through conduction, convection and radiation, which take place simultaneously affecting each other in very different ways. Each building component such as wall, floor, window and ceiling exchanges heat among one another. This multiple heat transfer process also takes place with the objects, pieces of furniture, machines, lamps, animals and individuals. These heat exchanges are complex and determine that a comfortable design cannot be predicted accurately. Even if HVAC machines are often over designed and provided with an on-off control, it is well-known that these machines, while working at their full capacity, cannot always cope with the thermal loads imposed on them. The subject of reducing thermal loads by means of passive techniques is in itself a very complicated issue, which is generally only addressed laterally and empirically, not based on rigorous analyses.

The need to be able to predict, with reasonable accuracy, the thermal response of a house or building under certain weather conditions and with a particular operation policy requires that the expected thermal mass be estimated before with precision. This exercise is hereby addressed in a light and modern building in Mexico City (Fig. 1). The precise nature and magnitude of the principal heat transfer phenomena must be appreciated. In fact, the individual heat flows and temperatures are of lesser relevance that an overall appraisal of the comfort indexes. Hence, a simplification can be made such that a lumped parameter model represents with the required precision and flexibility the phenomena under study.

2. Physical bases

The comfort temperature can be visualized as the mean or average temperature to which the individual user is exposed, regardless of other comfort variables such as air velocity, infrared radiation or humidity. The thermal flows are responsible for the variations in the inside temperature as described by the first law of thermodynamics:

$$M\,C_p \frac{dT}{dt} = Q_1 + Q_2 + \ldots + Q_n \qquad (1)$$

In Eq. (1), the product of the mass and the specific heat MC_p multiplied by the variation of temperature with time is equal to the total sum of all each individual heat flows into and out of the thermal system. Each heat flow Q is sustained between the inside air and each of the building components, objects, furniture and living beings inside the dwelling. One of those heat flows corresponds to the exchange with the ambient.

When this last heat flow prevails the temperature inside the dwelling follows very clearly the ambient temperature, In this case, the contribution of other heat flows is negligible. In the more general case, since interior temperature, T_i is related to the numerous heat transfer processes described above, its variation in time can be described by

$$\frac{dT_i}{dt} = \frac{UA}{M\,C_p}(T_i - T_a) \qquad (2)$$

In Eq. (2), the product of the overall heat transfer coefficient U times the heat transfer area A and then divided by M, C_p refers to the total processes of heat transfer that affect the relevant temperature T_i and can be approximated by

$$K_t = \frac{UA}{M\,C_p} = \frac{1}{n}\sum_n \frac{U_j A_j}{M_j C_j} \quad \text{for } 0 \le j \le n \qquad (3)$$

In this equation, the n processes of heat transfer take place with respect to the analyzed temperature T_i in such a way that the reference temperature T_a is representative of all relevant processes.

The interesting feature is that it is possible to write a lumped parameter model that should be capable of precisely reproducing the variations of T_i if a proper value for the effective thermal conductance K_t can be found. It is important to note that a particular house or office might have a very large number of parts and objects, each with its own K_t. However, it may be assumed that the largest and most relevant of those might be overwhelming, and are those in which the designer might be most interested. Those parts might not vary very much from one season to another, or with the introduction of other objects, and might determine the way in which the internal temperature evolves in time.

A given house or building for which the particular value of K_t is known will have a very well-known response to the reference temperature. In many cases, the reference temperature can be the ambient temperature in the vicinity of the hose under study. The effect of the heat transfer among the components of the house or office is both to attenuate the temperature variations inside the house and to provide a delayed effect in the inside temperature. A graphic representation of the most common case is given in