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A study of building envelope and thermal mass requirements for achieving thermal autonomy in an office building

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ABSTRACT

It is common knowledge that buildings should be constructed with good envelopes and sufficient masses. However, U.S. building codes make no provision for a building's thermal mass. This may result from that the conventional *heat balance* design—which assumes constant indoor air temperature, any heat imbalance resulting from corresponding envelope heat loss or gain and internal heat gain is accounted for by HVAC equipment—aims for HVAC selection, not for determining required building thermal qualities. We propose the concept of building thermal autonomy and a two-step *process assumption-based* design method. Thermal autonomy is a building's capability of keeping its indoor temperature sans HVAC equipment *within a prescribed temperature range*. The first step of the process assumption-based design method aims for the determination of building thermal qualities for a thermally autonomous building. Our finding shows that optimum slab thickness for a building's ceilings and floors is 25-cm and recommends 10-cm thick concrete slabs for its envelope walls. More interesting is the finding that climate-specific factor of diurnal temperature amplitude should be taken into consideration in the envelope design: a maximum WWR (Window-to-Wall Ratio) is given as a function of diurnal temperature amplitude.

1. Introduction

A building's envelope thermal resistance and its thermal mass are two most important passive elements for its thermal-control (thermal-management). The benefit of using high thermal resistance envelope in buildings is well-understood and research on superior envelope has been done extensively. The key idea is that in opting for superior envelope, the higher cost of the envelope can be mitigated with cost saving in HVAC equipment. Here are two well-known examples: The Passive House (Passivhaus) concept [1] popular in Europe requires very well-insulated exterior envelope, superior low U-value windows, strict airtightness, mechanical ventilation with heat recovery, and absence of thermal bridges; In its Standard 90.1 [2–5], the American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE) has progressively upgraded the permitted minimum thermal resistance of building envelope.

In contrast with the specified minimum requirements in envelope thermal resistance, there is no *quantitative* requirement in Standards, Codes, and Guides for building thermal mass. "Thermal mass" is mentioned many times in the U.K. CIBSE Guide A [6], F [7] and L [8], but usually in the forms of general guiding descriptions, such as "make effective use of thermal mass," "make appropriate use of thermal mass" and "provide appropriate thermal mass." In the Approved Document L1A [9] of The Building Regulations 2010, which is adopted in England, one finds a term "Thermal mass parameter (TMP)" but with limited information. The ASHRAE Standard 90.1-2010 [4] contains the most up-to-date energy-efficiency requirements for both commercial and residential buildings, including requirements for envelope (ceilings, walls, windows, doors), lighting (skylights, lighting equipment), and mechanical equipment (HVAC systems), but only mentions "thermal mass" twice without any detail.

One possible reason that building codes make no provision for a building's thermal mass may be the widespread application of the Heat Balance (HB) method, which is extensively discussed in the *ASHRAE Handbook — Fundamentals*. [10] The popularity of HB

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method is a reflection of the professional role mechanical engineers see in the engineering of buildings in terms of two elements: (1) the thermal resistance of envelope's primary effect on heat loss/gain thus ASHRAE's role in standardizing building envelope *R*-values; (2) the imbalance resulting from this heat exchange (loss/gain) can be balanced with equipment thus the responsibility of mechanical engineers in selecting HVAC systems. There is a resulting separation in design steps in this understanding of engineers' professional role: once building envelope *R*-values are standardized or codified, the building envelope design can be left to architects at an earlier stage of the design process with the selection of equipment by mechanical engineers coming at a later stage.

However, building's thermal mass is such a cost-effective approach for controlling building temperatures that "appropriate use of thermal mass throughout your home can make a big difference to comfort and heating and cooling bills." [11] Building thermal mass can be classified as either exterior envelope mass (eEM), which functions as both a storage medium and a heat transfer medium, or interior thermal mass (iTM), which predominately functions as a storage medium. Thermal mass "has the ability to absorb (convectively and radiatively) and store heat energy during a warm period and to release heat energy during a cool period later." [12] One attractive solution of using thermal mass in buildings is the thermally activated building system (TABS) proposed by a Swiss engineer, Robert Meierhans, in the 1990s. [13,14] TABS combines hydronic radiant cooling with thermal mass (typically interior concrete slabs), and it has "gathered great momentum in Europe, especially in Switzerland and Germany." [15] The 2012 publication of ISO 11855 [16] standardizes the world-wide design and construction of TABS, which proves that interior thermal mass can be successfully activated with water (i.e., hydronic activation).

The successful use of activated thermal mass suggests the possibility of approaching the conditioning of buildings first with an architectural step, the idea of which originated from a 2013 paper, [15] in which the concept of *neutral* mean ambient temperature $(\bar{T}_0)_{neutral}$ was introduced. Consider an assumed sinusoidal diurnal variation in ambient hourly temperature $T_0(t)$, where ΔT_0 is the ambient temperature amplitude:

$$T_0(t) = \bar{T}_0 + \frac{1}{2}\Delta T_0 \sin\left(2\pi \frac{t[hr]}{24}\right) \tag{1}$$

$(\bar{T}_0)_{neutral}$ is defined as the mean ambient temperature level that the envelope heat transmission loss is balanced with internal heat gain so that no HVAC equipment operation is required. The paper then focused on the investigation of the architectural requirement in envelope resistance and thermal mass so that the indoor operative temperature stays within a given temperature range. This approach was also reported as a part of a doctoral thesis. [17]

That line of ad hoc approach is generalized here into what will be called the *process assumption-based* method (the Heat Balance method is a *load assumption-based* method): by formally conceiving the design as a two-step process with the first architectural step focusing on the indoor operative temperature *range* as the design constraint and the second mechanical-engineering step devoted to maintaining the indoor operative temperature *level* as the design objective. In this paper we focus on the first step: thermal autonomy in buildings. In this step, the condition of keeping the indoor temperature of a building sans HVAC equipment within a prescribed temperature range is applied for determining the required thermal qualities. A building that is able, while it is subjected to variation in ambient temperatures of a given amplitude, to meet the *T*-range constraint in indoor temperature without using HVAC equipment is called a thermally autonomous building. The paper first presents a brief review of the general heat equation consideration and how the heat balance design approach of ASHRAE is related to the general heat equation in Section 2. Section 3 recounts the Emden exemplum, which shows the difference between the load assumption-based model and the process assumption-based model and explains why a process assumption-based model necessitates the explicit consideration of a building's mass. Sections 4 and 5 demonstrate that only a process assumption-based model of the indoor built environment can identify the advantages of passively using thermal mass without its activation. The major findings of the paper are an optimal slab mass thickness for iTM and a proposed redefinition of thermal envelope, which are given in Sections 4 and 5 respectively. Section 6 gives a recapitulation of the two design philosophies, the *process* design philosophy and the heat balance design philosophy — and their implication in terms of the large energy and thermal resource issues. The paper closes with a summary of arguments and new findings.

Research on the second mechanical engineering step will be reported in several follow-up papers. [18–20] The goal of our investigation is to eventually lead to the quantitative-codification of thermal mass and WWR in building codes and also to create a new relationship between engineers and architects in the green architecture movement.

2. From sequential heat balance method to collaborative process assumption-based method

The general heat equation may be written as,

$$\dot{Q}_{gain} + \dot{Q}_{env-in} + \dot{m}_{\inf} c_p (T_{amb} - T_{in}) + \dot{Q}_{HVAC-system} = (C_p)_{in} \frac{dT_{in}}{dt} \tag{2}$$

where the first term is the rate of internal heat gain, the second and third terms together represent the rated of the heat gain through conduction and infiltration across the envelope, the last term on the left-hand-side is the rate of equipment heat input, and $(C_p)_{in}$ on the right-hand-side is the heat capacity of the "interior space" and dT_{in}/dt is the time variation of interior space temperature.

We begin with the ASHRAE's Heat Balance method, which is used to calculate the cooling and heating loads for HVAC equipment selection as shown in Fig. 1. [10] We shall call it the radiant-convective conditioning of air model, which views the built environment as a static object.

A simplified version of the above "Schematic of Heat Balance Processes in a Zone" Model is shown in Fig. 2. The difference in the simplified model from the ASHRAE Schematic is the treatment of the envelope. ASHRAE's treatment takes detailed heat transfer processes into consideration throughout the configuration of the envelope, including the conduction processes, convective processes on inside and outside surfaces of the envelope, and radiative processes of short-, medium-, and long-wavelength radiation, whereas, our envelope treatment, shown in Fig. 2, (more detailed consideration will be made in sections below) is a simple overall *R*-value or *U*-value. In addition, the implicit mass behind radiant surfaces of the ASHRAE schematic is shown explicitly in Fig. 2.

It is important to note that the ASHRAE method does account for the time-dependent radiative heat exchange among surfaces and their collective interaction with air through convection. Air temperature, however, is kept time-independent or static (see Eq. (4) below), and one finds in Ref. [10] that, "Typical practice for cooling is to design for indoor conditions of 24 °C db and a maximum of 50 to 65% rh. For heating, 20 °C db and 30% rh are common design values." That is, two fixed specified indoor temperatures are chosen, one corresponding to the cooling season, and another to the heating season.

The heat balance of air may be summarized as

$$\dot{Q}_{gain} + \dot{Q}_{env-in} + \dot{m}_{\inf} c_p (T_{amb} - T_{in}) + \dot{Q}_{HVAC-system} = 0 \tag{3}$$