Applied Energy 104 (2013) 791–800

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Modeling of TABS-based thermally manageable buildings in Simulink

Peizheng Ma [a,*], Lin-Shu Wang [a], Nianhua Guo [b]

[a] Department of Mechanical Engineering, Stony Brook University, Stony Brook, NY 11794-2300, United States
[b] Department of Asian and Asian American Studies, Stony Brook University, Stony Brook, NY 11794-5343, United States

HIGHLIGHTS

- An RC model of a TABS-equipped thermally manageable building is built in Simulink.
- Manageability requires correct selection of TABS thermal mass and envelope resistance.
- A manageable building with the right mass-envelope combination functions robustly.
- Operative temperature level can be maintained by low-power equipment as cooling tower.
- Operative temperature variation is primarily a function of thermal mass and resistance.

ARTICLE INFO

Article history:
Received 18 September 2012
Received in revised form 15 November 2012
Accepted 3 December 2012

Keywords:
Building energy modeling
TABS
Thermally manageable building
Radiant cooling
Thermal mass
Cooling tower

ABSTRACT

Since Willis Carrier's invention of air conditioning in 1911, we traditionally think about building conditioning in terms of the heating and cooling of a building's indoor air. A better idea is the heating and cooling of a building's mass. The latter has been called the radiant method, of which a most attractive strain is the thermally activated building systems (TABS) proposed by Robert Meierhans in 1990s. In this paper, a resistor–capacitor (RC) model is built in Matlab/Simulink for studying the system requirement of a TABS-equipped building-room. Specifically, what is the requirement in the envelope thermal resistance and activated TABS thermal mass of the room so that it is able to keep the room's indoor operative temperature within the comfort range with its surroundings at neutral mean ambient temperature? Systematic simulations show that at neutral ambient temperature, the room's manageability requires the correct selection of thermal mass at normal value and thermal resistance within minimum envelope resistance range (MERR). With its surroundings at above neutral ambient temperature, the room with the required mass-envelope combination functions robustly, albeit with a slightly larger operative temperature variation. We introduce the term thermally manageable building, defined as BUILDINGS THAT CAN BE MANAGED WITH OFF-PEAK EQUIPMENT, EITHER MECHANICAL EQUIPMENT (e.g., a chiller) OR (natural energy gradient driven) LOW-POWER EQUIPMENT (e.g., a cooling tower). Simulation results also show that while the mean operative temperature level is maintained by cooling equipment (mechanical or low-power one), the operative temperature variation is primarily a function of a building's thermal mass and a building's envelope thermal resistance and, only to a small extent, a weak function of mean ambient temperature and the diurnal temperature amplitude.

1. Introduction: machine vs. thermal mass

Archaeological remains of the Kurdish settlement Nevali Cori dated back 9000 years show evidence of an intermediate space below the floor which was flooded with water from a nearby creek for summer cooling [1]. Ancient Greece and Rome were known to use Hypocaust [2], an under-floor heating system. These were examples of radiant conditioning. Even the use of fire in fireplaces and stoves is examples of radiant and convective heating.

Willis H. Carrier's invention of air conditioning in 1911 changed the practice from a multitude of radiant-convective conditioning methods to the method of convective conditioning of air alone. Undoubtedly Carrier's success was an example of Machine Age's triumph, and the initial success in air cooling evolved into air cooling and heating with HVAC mechanical devices. The success and its contribution towards human comfort in built environment, however, came with a cost. The over-use of "one size fits all" mechanical solutions, rather than the design of buildings themselves, for building's thermal conditioning led in the 20th century to profligate energy consumption.

The idea of thinking in terms of a system and the physical building itself as an integral part of the whole building system is

* Corresponding author.
E-mail addresses: peizheng.ma@stonybrook.edu (P. Ma), lin-shu.wang@stonybrook.edu (L.-S. Wang), nianhua.guo@stonybrook.edu (N. Guo).

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.12.006

becoming true again today. For instance Harvey [3] noted, "the energy use of buildings depends to a significant extent on how the various energy-use devices are put together as systems, rather than depending on the efficiencies of the individual devices. The saving opportunities at the system level are generally many times what can be achieved at the device level ..." In the context of system thinking, it is relevant to ask, "What is being heated or cooled?" Since 1911, we traditionally think about building conditioning in terms of the heating and cooling of a building's indoor air. Instead air, a better, "back to the future" idea will be the heating and cooling of a building's mass, which can store much greater quantity of heat or coolness than air. We may call the former the convective method and the latter the radiant method. Only the latter involves physical building directly. The fact that water is a much more effective heat transfer medium alone brings about typically a 43.4% (36% + 7.4%) energy saving, as shown in Fig. 1 [4,5].

A common misconception is that radiant heating requires high temperature source, or radiant conditioning requires large temperature difference (or gradient). The fact is exactly the opposite: "The radiant heating and cooling system supply water temperature would typically operate at a temperature [set points of] less than 180 °F for heating and greater than 45 °F for cooling, which [180 °F and 45 °F] are typical supply water temperatures for a traditional forced air system. The central-plant heating and cooling equipment can operate more efficiently at these temperature set points" [6]. This is because a radiantly conditioned space is enclosed by a large area of surfaces with the resulting heat exchange being dependent on both the large area and the temperature difference – which can be small due to the large surface area for the required heat exchange. A most attractive strain of radiant cooling is thermally activated building systems (TABS), which was first proposed by the Swiss engineer Meierhans [7].

Water for activating the thermal mass of a TABS-based, radiantly cooled building can be conditioned by mechanical chiller ("central-plant cooling equipment"), powered by mechanical energy. Or, it can be conditioned by cooling tower driven by natural energy gradient (or moderately high temperature, i.e., not very

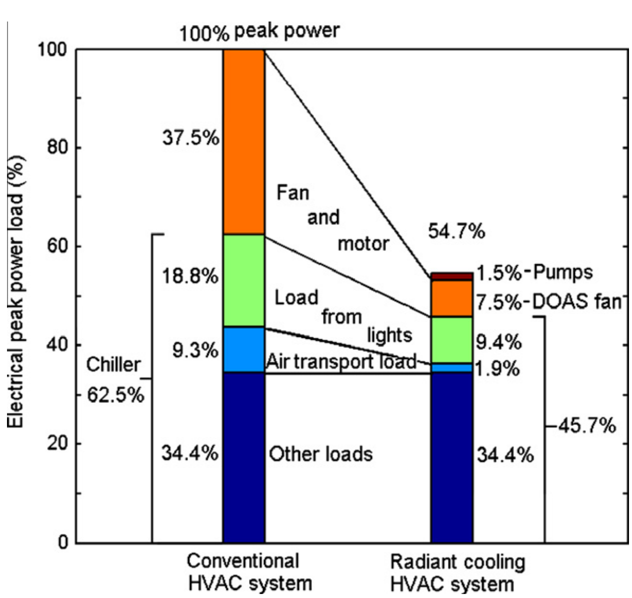

Fig. 1. Comparison of electrical peak power load for conventional systems and radiant cooling systems. The radiant cooling system reduces power demand by pumping chilled water to provide radiant cooling, rather than by blowing chilled air. A direct saving of 36% (37.5–1.5%) in air fan power requirement is shown. As well as an indirect saving due to lower Air Transport Load (heat gain due to fan operation). Percentages are relative to overall peak power for the conventional system.

low temperature [above 45 °F], coolness); the cooling tower requires low-power (lower mechanical energy power). Radiantly conditioned buildings require, in addition to large TABS thermal mass, a good-performance envelope, a well-known fact but one that has not been systematically studied. This paper carries out the systematic, quantitative determination of the functional relationship of building indoor operative temperature in terms of activated thermal mass and envelope thermal resistance. The investigation here is based on a resistor–capacitor (RC) model, which has been used in several previous papers for modeling thermal systems (see Sections 2, 3 and 5), using the tool of Matlab/Simulink.

Section 2 gives the literature review briefly. Section 3 presents the schematics of the thermal activation of building thermal mass. Section 4 lists several useful concepts and definitions. Section 5 presents the RC modeling of a TABS-equipped room, as well as the simulation results of two basic cases. Section 6 considers the simulation results of a building model at neutral mean ambient temperature, i.e., mean ambient temperature that the building with sufficient thermal mass and adequate envelope thermal resistance requires no or little cooling. Section 7 places the building at mean ambient temperature higher than the neutral temperature; it concludes that a building with the right mass-envelope combination functions robustly with its indoor operative temperature staying within a small range.

This suggests the concept of thermally manageable building mass-envelope, which is defined as BUILDINGS THAT CAN BE MANAGED WITH OFF-PEAK EQUIPMENT, EITHER MECHANICAL EQUIPMENT (e.g., a chiller) OR (natural energy gradient driven) LOW-POWER EQUIPMENT for controlling operative temperature level. Despite the sub-heading of this section this paper does not argue against the use of machine, only the overuse of high-power mechanical equipment.

We close with a brief conclusion in Section 8. This paper does not examine the design selection of cooling tower and the availability of adequate variation in hourly ambient temperature: both are simply assumed to be available and adequate in Section 7. The design selection of cooling tower low-power equipment (lowPE) on the basis of design ambient temperature and design variation-range in hourly ambient temperature is presented in another paper [8]. Design selection of other kinds of lowPE will be presented in future papers.

2. Literature review

2.1. Thermally activated building systems (TABS)

The practice of thermally activating building mass was originally established by a Swiss engineer – Robert Meierhans in 1990s. Meierhans published two important research papers entitled *Slab cooling and earth coupling* [7] in 1993 and *Room air conditioning by means of overnight cooling of the concrete ceiling* [9] in 1996. In the first paper, an office building with ceiling slab cooling system in Horgen, Switzerland, was introduced. Simulation results showed that cooling load was shifted into night hours. The author pointed out that "the slab cooling system ... combines the advantages of radiant cooling with the thermal storage of massive concrete ceilings". In the second paper, the operating data of the office building in the first paper was reported showing that the slab cooling system had proven successful over a period of three summers. Comfort measurements in actual and under load-simulated operating conditions confirmed the suitability of the system for small and medium loads.

With architect Peter Zumthor, Meierhans developed two hugely successful projects [10,11] on the *Thermal Bath at Vals* in Switzerland (1996) and the *Kunsthaus Bregenz* in Bregenz, Austria