Applied Energy 127 (2014) 172–181

Contents lists available at ScienceDirect

Applied Energy

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

Modeling of hydronic radiant cooling of a thermally homeostatic building using a parametric cooling tower

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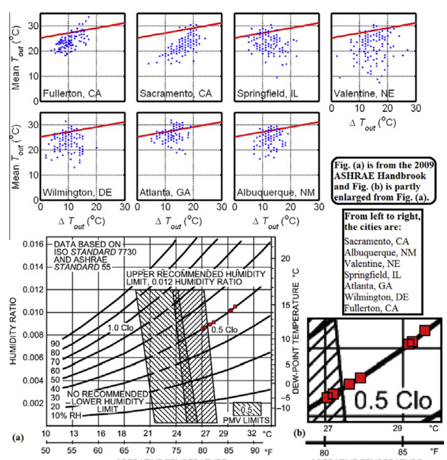
HIGHLIGHTS

- Investigated cooling of thermally homeostatic buildings in 7 U.S. cities by modeling.
- Natural energy is harnessed by cooling tower to extract heat for building cooling.
- Systematically studied possibility and conditions of using cooling tower in buildings.
- Diurnal ambient temperature amplitude is taken into account in cooling tower cooling.
- Homeostatic building cooling is possible in locations with large ambient *T* amplitude.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 October 2013
Received in revised form 24 February 2014
Accepted 10 April 2014
Available online 4 May 2014

Keywords:
Heat extraction principle
Building energy modeling
Radiant cooling
TABS
Cooling tower
Thermally homeostatic building

ABSTRACT

A case is made that while it is important to mitigate dissipative losses associated with heat dissipation and mechanical/electrical resistance for engineering efficiency gain, the "architect" of energy efficiency is the conception of best heat extraction frameworks—which determine the realm of possible efficiency. This precept is applied to building energy efficiency here. Following a proposed process assumption-based design method, which was used for determining the required thermal qualities of building thermal autonomy, this paper continues this line of investigation and applies heat extraction approach investigating the extent of building partial homeostasis and the possibility of full homeostasis by using cooling tower in one summer in seven selected U.S. cities. Cooling tower heat extraction is applied parametrically to hydronically activated radiant-surfaces model-buildings. Instead of sizing equipment as a function of design peak hourly temperature as it is done in heat balance design-approach of selecting HVAC equipment, it is shown that the conditions of using cooling tower depend on both "design-peak" daily-mean temperature and the distribution of diurnal range in hourly temperature (i.e., diurnal temperature amplitude). Our study indicates that homeostatic building with natural cooling (by cooling tower alone) is possible only in locations of special meso-scale climatic condition such as Sacramento, CA. In other locations the use of cooling tower alone can only achieve homeostasis partially.

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http://dx.doi.org/10.1016/j.apenergy.2014.04.031
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1. Introduction

In a Foreword to Heating, Cooling, Lighting [1] the architect J.M. Fitch wrote, "The central paradox [challenge] of architecture [is] how to provide a stable, predetermined internal environment in an external environment that is in constant flux across time and space..." We want to argue that the changing external environment is both a challenge and an opportunity—a challenge in the architectural design of a building for achieving partial independence from the ambient environment and, at the same time, an opportunity in the engineering of the building for harnessing natural temporal and spatial energy gradient in its interaction with the ambient environment.

One of the main challenges imposed by variable environment is the cooling and heating load-demand on a building. Heat Balance design sees a building in terms of its loads—which are functions of the specific indoor air temperature [2,3] and the weather ambient temperatures, with envelope heat transmission performance as the parameter. These loads are to be balanced with HVAC equipment. If the HVAC equipment is to guarantee thermal comfort at all time, it must be designed for peak weather ambient temperatures. Since any extreme weather condition is a statistical possibility, it would not be practical to aim for the most extreme but transitory condition (which would lead to over-sizing of equipment). The design of equipment is therefore based on fixed climatic design [peak] conditions, which for annual cooling according to the 2009 ASHRAE Handbook – Fundamentals [3] is the design condition for 0.4% or the design condition for 1% or the design condition for 2% in annual cumulative frequency of occurrence (exceeding the design condition). There are 365×24 h = 8760 h in one year. The 0.4%, 1%, and 2% design conditions are the three dry-bulb temperatures values that the instantaneous hourly temperature in the hottest months exceeded the corresponding value for a duration of 35 h (0.4% of 8760 h), 88 h (1%), or 175 h (2%) per year, respectively, for the period of record. For convenience the following discussion will be based on 1% dry-bulb temperatures or $(T_{out})_{design\_1\%}$.

Notice that the climatic design conditions for conventional HVAC selection—design condition for 1%—are the peak values of hourly temperature T_{out}, not diurnal average temperature $\overline{T}_{out}$. (For simplicity, in this discussion the conventional load is said to be based on peak hourly value in the steady-state sense. Overlooked are the various refinements of the conventional load calculations by taking into consideration of the temporal thermal response of a building.) Let the peak-to-peak amplitude of the diurnal temperature variation be ΔT_{out}, the peak hourly temperature T_{out} and the daily mean temperature $\overline{T}_{out}$ are related as:

$$T_{out} = \overline{T}_{out} + \frac{1}{2}\Delta T_{out} \tag{1}$$

The peak hourly temperature T_{out}, which is the determinant of the equipment capacity and the driver (causation) of the irreversible heat transfer process, depends on (and increases with) both the daily mean temperature and its amplitude: both are parts of the changing external environment: high value of $\overline{T}_{out}$ and high value of ΔT_{out} both contribute to the cooling load in the operation of a building.

Rather than the heat balance design which sees a building in terms of its energy demand, a new two-step process assumption-based design method [4–7] sees a building in terms of its autonomous and homeostatic existence. We use here the term autonomous in the narrow sense of a building's ability of staying within a specific temperature range passively [5–7], but not at a given temperature level (homeostasis), which requires active control (the topic of this paper). By considering building energy as a building thermal processes problem, the central argument of this paper is that buildings' external environment represents both a challenge of maintaining autonomy [5,7] and a driving force for contributing to buildings' homeostasis by the application of heat extraction principle. This paper is limited to only the cooling phase of homeostasis by heat extraction. Heat can be extracted by heat pumps, or cooling towers, or solar thermal panels. Investigation along the use of heat pumps (for cooling and heating) and solar thermal panels (for heating phase) will be conducted elsewhere. Instead, this paper addresses the use of cooling tower for extracting heat from indoor thermal mass for controlling indoor operative temperature level.

A parametric cooling tower is added to the RC (resistor–capacitor) model built in Matlab and Simulink used in Refs. [4–7] to harness the natural energy gradient driven force for the building-room cooling. It will also give a discussion of the hypothetical design selection of cooling tower: instead of dependency on the single peak hourly temperature T_{out}, it will be shown that the design conditions are function of both the diurnal average temperature $\overline{T}_{out}$ and the amplitude of the diurnal temperature variation ΔT_{out}, with quite different functional relationships for the two. At last, how a building function under climatic conditions of different locations will be studied. This paper is a study following the development of Refs. [4–8], and represents the first paper on engineering for building homeostasis.

A few words on thermodynamics of building systems and the importance of heat extraction for efficient operation of building systems are given below to put this paper's content in the context of our overarching approach to building energy efficiency: This paper is one element in the goal of reducing waste heat from the cooling and heating operation (i.e., conditioning) of building systems, which is the sound scientific and engineering approach for successful building design for energy efficiency.

2. Thermodynamics of the operation of building systems

Design and the refinement of heat engines and heat pumps have been based on the science of thermodynamics, which was founded by Carnot, critically developed by Thomson, and refined and made productive applications by generations of engineers including Otto and Diesel, Whittle and Von Ohain, Carrier, Keenan, etc. Heat engines and heat pumps are powered by fuel input (or heat input) for producing well-defined outputs, work or power in the former case, and, in the latter case, heat to be removed or heat to be delivered. Thermal efficiency of heat engines and coefficient of performance (COP) of heat pumps are properly defined.

In contrast, whereas buildings or building systems are well defined, there is no "output" of a building: a building exists and we construct a building not for anything it produces but for its existence at certain indoor conditions we prefer. There is thus no yardstick for measuring the performance of a building in the same objective or scientific way we measure heat engines and heat pumps. We know how a perfect heat engine (even only as an abstraction) could perform and that is the way we measure objectively a real heat engine's performance. We did not have an idea of how a building with perfect cooling and heating operation should perform—until today.

Because we did not have a good answer to that question it is not surprising that building energy efficiency has not gained as it has been hoped for: "These 121 LEED buildings [with available energy performance data] consume more total energy per square foot than the average for the entire commercial building stock," APS concluded in its 2008 study [9]; "Whereas the US has made significant progress in increasing efficiency and reducing energy use in the transportation and industrial sectors of the economy, both building sector energy use and building system energy use have shown only