Energy and Buildings 120 (2016) 135–144

Contents lists available at ScienceDirect

Energy and Buildings

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

A bi-directional systematic design approach to energy optimization for energy-efficient buildings

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ARTICLE INFO

Article history:
Received 8 November 2015
Received in revised form 14 February 2016
Accepted 25 March 2016
Available online 26 March 2016

Keywords:
Bi-directional systematic methodology
Energy optimization
HVAC system
Building thermal load
System efficiency
Cooling-to-heating load/energy ratio
Primary energy consumption

ABSTRACT

A new bi-directional systematic methodology was developed to minimize the building thermal load and energy consumption using cooling-to-heating load ratio and system efficiency to select optimal sets of building design factors and HVAC systems. On the basis of simulations conducted on a total of 384 combinations of HVAC system and alternative building models, the correlation between building cooling-to-heating load ratio and HVAC system energy consumption was analyzed. The diverse and total cooling and heating system efficiency of HVAC systems was derived. It was found that the ratio of the efficiencies of heating and cooling systems affected the optimum building design, hence the active and passive parts of a building should be considered simultaneously in a coupled way for the optimum design for the energy-efficient buildings. Energy consumption tends to vary radically with the type of HVAC system, even under identical building load conditions. That is, with different cooling-to-heating load ratio but a similar total energy, the total primary energy consumption and the cooling-to-heating energy ratio are predicted to change depending on the selected HVAC system. It is expected that a design plan formulated using the method and system efficiency enable a bi-directional energy optimization process conducive to providing feedback and prove to be of great use in building design factors, HVAC system solution, and decision-making at the initial design stage that considers building thermal load characteristics.

1. Introduction

On a global scale, energy-saving policies aimed at greenhouse gas and environmental load reductions are no longer an option, but are now rather a requisite for a nation's policies. Korea has finalized its 2030 target of reducing greenhouse gas emissions by 37% from business-as-usual (BAU) levels. Even the construction sector was up to 24% in the most recent consumption outlook, and obligations for "zero-energy" building construction are set to begin in 2020. Global building energy policies provide the Korean industry and economy with a chance to build new business models. Pérez-Lombard et al. [1] showed that the energy consumption of a modern building's heating, ventilation and air-conditioning (HVAC) system has steadily been increasing, comprising more than half of its entire energy consumption. Shahrestani et al. [2] and Elovitz [3] discuss the design of an HVAC system that is determined at the initial stage of the building design process, a decision that has a definite impact on the building's energy performance, thermal comfort, and operation cost. For this reason, recent years have witnessed increasing uses in optimization methods for HVAC system solution for effective energy saving. With the advancement in computer technology, sophisticated engineering analysis methods have become prevalent. As a result, with the aid of existing commercial building energy simulations, a number of researchers [4–6] have developed optimization tools by coupling energy consumption and life cycle cost (LCC) with a range of building elements.

Yang et al. [7] stressed that the utilization of energy simulation tools, despite their precision, requires expert knowledge, meticulous understanding of input variables, and a considerable amount of time. At the working level, therefore, there is a constant need for the development of a tool that is easy and convenient to use at the early design stage. By analyzing the minimum baseline HVAC system and employing a comparative evaluation method, Cho et al. [8] developed a tool that overcomes the existing drawbacks and enables the examination of the energy consumption and economic feasibility of various system combinations and made available for the decision-making process at the design stage. The energy performance of a building, varying with its design and operation methods, is also determined by the interactions of various building design elements (passive design) and the HVAC system

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http://dx.doi.org/10.1016/j.enbuild.2016.03.066

Nomenclature

E	Primary energy consumption [kWh]
Q	Building thermal load (demand) [kWh]
L	Energy losses [kWh]
η	System efficiency of HVAC
t	Annual operating hours [h]
PLR	Part-load ratio
Superscripts	
P	Peak
A	Annual
A/C	Air-conditioning system
Plant	Plant system
Subscripts	
c	Cooling
h	Heating

(active system). As a consequence, Hayter et al. [9] obtained a result that the concept of integrated design based on a combination of HVAC systems has become increasingly important, although optimization at each stage is also deemed significant. Pantelic et al. [10], Wemhoff [11] and Kong et al. [12] have been conducted on multi-objective optimization methods that take into consideration indoor thermal comfort as well as energy consumption and cost in recent years. However, the large body of building energy optimization studies, performed for a variety of purposes and needs, has numerous limitations in their application to actual projects. In the existing building design process, architectural planning and HVAC system design were allowed to proceed unidirectionally and independently of each other while maintaining only a marginal relationship, and thus their implementation timing was disparate. In other words, HVAC system design was not typically initiated until the completion of architectural design, which either led to the omission of a feedback process where mutual impact is examined or left too little time for such a feedback process. For the same reason, energy performance optimization for architectural elements and for an HVAC system was formulated separately.

The method mainly used was aimed at minimizing building energy requirements and thermal load on the basis of architectural elements and then producing an optimal alternative via the HVAC system solution and energy efficiency enhancement. Due to institutional and legal regulations and demands from clients, however, there were frequent cases where optimization could not be attained in a reasonable manner. Caused in part by the unidirectionality of the design process, this limitation also stemmed from the lack of accurate information on how architectural elements and thermal load are optimized depending on HVAC system design conditions. Unlike the existing method for building energy optimization factoring in a quantitative aspect alone, that is, the aggregate of building cooling and heating load, a new method should take into account the HVAC system composition for the purpose of building energy analysis, since the composition is affected by both the quantitative aspect and the ratio of building cooling and healing load. So far, no method has been proposed that achieves energy optimization by computing energy with the building cooling-to-heating load ratio reflected in the HVAC design process and by controlling building thermal load elements on the basis of feedback from the computation. Therefore, this study seeks to derive comprehensive information on overall HVAC system efficiency that makes it possible to select a HVAC system based on the cooling-to-heating load ratio and in turn provide feedback for architectural design. The significance of the study lies in the possibility of forming a reasonable system alternative through gaining a grasp at the design stage of energy performance specific to each HVAC system.

2. Correlation between building thermal load and energy consumption

Buildings consistently consume energy to maintain indoor environment conditions. Throughout the year, various patterns and sizes of building thermal load (cooling and heating) are determined by the external environment (such as climate, location, and surrounding buildings) and the indoor environment (conditions in individual rooms). An HVAC system needs to eliminate such building thermal load, and remove or provide heat as it consumes energy in accordance with the degree of building cooling and heating load. Cho et al. [8] and Perez-Lombard et al. [13] showed that an HVAC system is made up of various combinations of air-conditioning systems, distribution systems, and plant systems, and its energy consumption is determined by its combination and system efficiency. Generally, as indicated in Eqs. (1)–(3), the primary energy consumption of a building's HVAC system is proportional to the building's annual load [14]. The cooling-to-heating load ratio eventually converts back into the cooling-to-heating energy consumption ratio. Primary energy consumption varies with the source energy (electricity, LNG or district heat) and the equipment efficiency of cooling and heating plant systems.

$$E_c = \frac{\sum Q_c^A}{\eta_c} \tag{1}$$

$$E_h = \frac{\sum Q_h^A}{\eta_h} \tag{2}$$

$$E = E_c + E_h = \frac{\sum Q_c^A}{\eta_c} + \frac{\sum Q_h^A}{\eta_h} \tag{3}$$

Therefore, the energy consumption of buildings, even with similar total thermal load and identical HVAC systems, may differ depending on their cooling-to-heating load ratio. Building energy optimization can be obtained by strategically implementing passive design. The availability of information on the overall efficiency of each HVAC system makes it possible to achieve the quantitative and proportional optimization of building thermal load and, in turn, the minimization of energy consumption. Through the process presented in Fig. 1, this study analyzes the way an HVAC system's primary energy consumption varies with cooling-to-heating load ratio on the basis of architectural design conditions with a similar building thermal load. It then determines the overall efficiency for various HVAC systems in order to guide the direction of building design and system efficiency information targeted at cooling-to-heating load ratio optimization by drawing on the previously selected HVAC system. Building thermal load is estimated with the use of TRNSYS, a commercial simulation software, while HVAC system primary energy consumption is analyzed using HVAC system energy evaluation tool (HEET), a tool for making multiple predictions of HVAC system energy evaluation [8]. HEET is an analysis tool capable of simultaneously computing the primary energy consumption of various HVAC system combinations under identical architectural conditions (identical building thermal load), and can be run in tandem with the TRNSYS simulation program. For the conditions and the method for interpreting the system's optimization model, the input of basic information concerning building load and climate data enables the interpretation of the baseline system, which serves as the evaluation criteria of all systems. Based on the input data, an energy analysis of 33 base HVAC systems is performed, and the energy consumption ratio of each base HVAC's plant system, air-conditioning system, and distribution system to the baseline system is then calculated. Energy analy-