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Energy and Buildings 37 (2005) 37–48
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Energy-efficient envelope design for high-rise apartments

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Received 25 March 2004; received in revised form 27 April 2004; accepted 6 May 2004

Abstract

The energy required to create a comfortable living environment in high-density cities in hot and humid climates usually demands a substantial electricity usage with an associated environmental burden. This paper describes an integrated passive design approach to reduce the cooling requirement for high-rise apartments through an improved building envelope design. The results show that a saving of 31.4% in annual required cooling energy and 36.8% in the peak cooling load for the BASECASE apartment can be achieved with this approach. However, all the passive strategies have marginal effect on latent cooling load, often less than 1%.

Keywords: High-rise apartments; Hong Kong; BASECASE model; TRNSYS; Envelope design; Thermal simulation; Green architecture; Energy efficient building

1. Introduction

The rapid economic development and the high population densities of many Southeast Asian countries and China have created a number of cities dominated by high-rise apartment buildings. Hong Kong is one of the most well-known examples of this type of city. About 90% of its total population live in high-rise buildings and half of these are in densely built-up public housing estates [1]. The increase in electricity consumption by the residential sector, particularly in the summer months, has been caused by the growing demand for air-conditioning systems to provide thermal comfort for the occupants [2]. The ownership of air-conditioners has risen from 50% in 1989 to 90% per household in 1993 [3]. This phenomenon suggests that there is a potential to reduce the energy consumption and resultant greenhouse gas emissions by reducing the need for air-conditioning in apartment buildings. Local building designers have largely ignored passive design strategies, which can moderate internal temperatures and hence reduce building energy consumption by adjusting the building to match the local climatic forces. Most previous passive design studies have focused on houses and commercial buildings in moderate, cold or hot arid climates.

This paper describes an investigation of the effect of six passive design strategies, namely, insulation, thermal mass, glazing type, window size, colour of external wall and external shading devices, on both the annual required cooling energy and peak cooling load on a high-rise apartment building in Hong Kong. This study quantifies the energy savings and improvement in human comfort if these passive strategies are integrated into such buildings. The paper begins with a general overview of the climate in Hong Kong and then reviews previous research into the use of passive design strategies on high-rise buildings in this climate. The model used to simulate the strategies is then described, followed by the results and conclusions of the investigation.

2. Climatic conditions in Hong Kong

Hong Kong is located at the latitude 22° 18′ N and longitude 114° 10′ E, and he climate is classified as sub-tropical. In the winter months (November–February), the mean temperature is approximately 15–18 °C. According to the Hong Kong Observatory [4], it is not uncommon for temperatures to drop below 10 °C in urban areas, and the lowest temperature recorded at the Observatory is 0 °C, although sub-zero temperatures and frost occur at times on high ground and in the new territories. The spring season is short, humid and sometimes very foggy. The temperature also tends to fluctuate widely from day to day. In the summer months, between May and September, the weather is mainly tropical, i.e. hot and humid with occasional showers or thunderstorms. Afternoon temperatures frequently exceed 32 °C between June and September, with the mean temperature around 27–29 °C. The autumn season is short and lasts only

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doi:10.1016/j.enbuild.2004.05.002

from mid-September to early November. The mean annual rainfall is about 2225 mm of which 80% falls between May and September. The hot and humid long summer season of Hong Kong creates a huge demand for air-conditioning for comfort cooling.

3. Previous research

There is only a limited amount of research literature on energy-efficient apartment building design in hot and humid climates. Most of the literature in the Southeast Asian region has focused on comfort conditions for building occupants [5,6], while the majority of apartment design-related studies have been conducted in Hong Kong. Lam [7] reported a study in 1993, which investigated the impact of glazing type, external shading and wall insulation on energy consumption. However, the apartment size studied was too large (160 m^2) compared to the majority of current apartments in Hong Kong (55 m^2). In the model used, the layout of floor plan is oversimplified, the living room window is too large and no window is provided in the kitchen, bathroom or laundry. The other shortfall is that only north- and south-facing windows are included in the model, which does not correspond with the majority of eight flat-per-floor designs currently seen in Hong Kong. Lam's study also did not consider the possibility of natural ventilation. Higgs [8] reported another study in 1994, which investigated the effects of self-shading on the cooling load and energy consumption. This study showed that self-shading reduced both the peak cooling load and energy consumption of south- and west-facing apartments by more than 15%. However, this study did not incorporate any occupancy schedule or internal loads for the flats and assumed that all rooms were conditioned continuously. This assumption is likely to distort the result and hence reduce the validity of this study. Another study [3] in 2000 focused on the electricity consumption and the current design of high-rise residential buildings. It contained valuable information of the various design characteristics of high-rise apartment buildings, which has been used in the present study. The paper also predicted the energy saving by introducing 25 mm insulation and replacing all windows with tinted glass. Unfortunately, the area of the apartments and the occupancy schedules were not reported and therefore the applicability of the results is limited.

Bojic et al. [9] investigated the influence of wall insulation thickness and its position in the building envelope on peak cooling load and energy consumption. The study showed that cooling energy consumption could be reduced by approximately 7% by placing thermal insulation on the outside of the envelope walls. Although this study provided detailed results on the relationship between thickness and position of thermal insulation in the envelope wall, it only studied south-facing apartments. The operating schedule of plug loads in kitchen also limited the applicability of the study. The schedule used a 518 W/m^2 plug load in the kitchen between the hours 21:00 and 00:00, although the kitchen was deemed to be unoccupied at the time with no lights were switched on.

In a subsequent study by Bojic et al. [10], the same thermal model was used to evaluate the influence of insulation in internal partitions. The results indicated that there is a substantial energy-saving potential when insulation is used in the partition wall between the kitchen and the living room, but this again indicated that perhaps an unrealistic heating load had been assumed for the kitchen. The same authors later investigated the effects of the shading coefficient of windows on peak cooling load and energy consumption using the same building model [11]. This study reported the effect of orientation on energy consumption. Only a generic glazing type was investigated in which the only variable is the shading coefficient. In reality, the shading coefficient is not the only property of a glazing system that affects the indoor climate. The thermal transmittance and thermal capacitance are also influential properties, especially when the flats are occupied at night and where solar gain through windows only occurs during a minor part of the occupied hours.

Generally speaking, previous studies have focused only on a particular envelope component in a generic building. There is a lack of comparative study of the relative efficiency and impact of passive design strategies. However, the above studies provided resources for this research, such as input parameters and benchmarks for validations that are hard to obtain otherwise. The authors of the present study have previously investigated the effect of five low-energy building envelope design strategies, namely, wall insulation, glazing type, colour of external wall, window size and external shading, using the software ENERGY-10 [12]. The results indicated that up to 40% of annual required cooling energy could be saved. This study, however, also had some limitations. Firstly, the software used could not simulate the effect of natural ventilation during unoccupied hours. Secondly, the software could only simulate two thermal zones and thus the model was only able to simulate a living/dining and a bedroom zone. This arrangement ignored any inter-zonal thermal exchange, and the influence of the bathroom and kitchen. Finally, only a west-facing apartment was modelled and the energy saving achieved by each individual strategy was calculated, rather than assessing an integrated design, which combined the effects of all strategies.

4. The BASECASE model

The objective of the present investigation is to overcome the limitations of previous studies, and detailed building energy simulations have been carried out using the computer program TRNSYS [13]. A BASECASE building model of a representative building design was developed. It was decided to select a current building design used in Hong Kong as the BASECASE, rather than creating a generic design. The public rental flats being developed by the housing au-