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Proposal for optimum combination of reflectivity and insulation thickness of building exterior walls for annual thermal load in Japan

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ABSTRACT

This paper is a proposal to optimize the combination of surface reflectivity and the insulation thickness of exterior walls for energy savings in regions of Japan. Calculations of building thermal loads and economic analysis of the total cost for six cities from high-latitude to low-latitude regions of Japan were carried out for a range of surface reflectivity and insulation thickness of exterior walls. The results can be used in design to decrease the energy requirements of buildings. We estimated the annual thermal loads of a simulated building floor and analyzed the cost of the building envelope in Sapporo, Tokyo, Nagoya, Osaka, Fukuoka and Naha, Japan, varying the surface reflectivity of the exterior walls from 0.1 to 0.8, and insulation thickness of the exterior walls from 10 mm to 100 mm, using the thermal load calculation software, New HASP/ACLD-β and cost analysis. Optimum combinations of surface reflectivity and insulation thickness for each region are proposed.

1. Introduction

At present, the energy demands of buildings are high due to the indoor thermal comfort requirements of buildings. Research of highly reflective (HR) materials used for roof or façade of buildings [1–3] and retro-reflective (RR) building envelopes [4–6], has shown that HR or RR building coatings can reduce the cooling load in the summer due to their high reflectivity. However it can increase the heating load in the winter [7,8]. Insulation in exterior walls can decrease the heat loss or gain through the building envelopes in the winter, but at increasing cost. Design and construction with optimal insulation should be considered as a prerequisite and a top priority for energy savings in buildings [9]. The definition of optimum insulation thickness has been detailed by many researchers [10–12]. The degree-day method is well known to calculate the energy needs of buildings, and methods of calculating the optimum insulation thickness are proposed based on the degree-day method [13–15].

The global contribution from buildings towards energy consumption, both residential and commercial, has steadily increased to between 20% and 40% in developed countries, and has exceeded the other major sectors: industrial and transportation [16]. Buildings in the urban area are a major contributor to the urban heat island (UHI) phenomenon. Focusing on the anthropogenic heat emissions, a study showed that exhaust heat from buildings in Japan accounted for approximately half of the anthropogenic heat in the city [17]. Thus, reducing energy consumption in buildings plays an important role in countering the UHI effect.

The building envelope plays a significant role in optimizing indoor temperatures as a thermal barrier. Also, the building envelope affects the cooling peaks and air conditioning system capacity requirements. The thermal properties of the building envelope are determined by the combination of wall mass, thermal resistance, insulation thickness and location, exterior surface color, etc. [18]. The thermal insulation of building exterior walls significantly reduces the heating and cooling needs of the zone [19]. The influence of insulation configuration on thermal loads of buildings had been detailed by many researchers. Lee et al. [20], conducted a research to study the performances of the heat and multilayer reflection insulators used for buildings in South Korea. The result showed that the multilayer reflection insulator keeps the indoor-side surface temperature high during winter or low in summer, enhances the comfort of the building occupants and reduces thermal loads. Kossecka and Kosny [21] carried out a study on the influence of insulation configuration on thermal loads of buildings and

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performed a whole-building energy modeling using DOE-2.1E to predict annual heating and cooling energy demand for a one-story residential building. Results showed that the material configuration of the exterior wall can significantly affect the annual thermal performance of the whole building under different types of climate. Ozel [22] used a numerical model to determine the annual thermal (cooling and heating) transmission loads, then inputted the calculated thermal transmission loads to an economic model to determine the optimum insulation thickness for a south-facing wall in the climatic conditions of Elazığ, Turkey. The solar absorptivity of exterior surface was evaluated from 0 to 1. The results indicated that the heating and total thermal loads decreased with increasing surface absorptivity. However, solar absorptivity has a very small effect on the optimum insulation thickness and payback period, but a more significant effect on energy savings.

The energy conservation of buildings and strategies of UHI mitigation consider both high thermal insulation and high reflection of exterior walls in Japan. In Japanese law the "Act on the Rational Use of Energy" set energy conservation standards and mandated insulation depending on one of six climate zones [23]. However this only applies to buildings of over 2000 m^2 floor area. The recent "Act for the Improvement of the Energy Saving Performance of Buildings" will mandate insulation in small buildings as well by 2020 [24]. However, there is lack of the research on the optimal combination of surface reflectivity and insulation thickness at present [25,26]. In order to contribute to the initial design, construction and refurbishment of building exterior walls, this paper aims at exploring the optimum exterior wall configurations with consideration of both the surface reflectivity and insulation thickness of exterior walls for six representative cities of Japan.

2. Representative cities and simulation building

From high-latitude to low-latitude, six representative cities of Japan were chosen to calculate the thermal load of simulation buildings, which is strongly related to energy consumption of buildings. The map of the chosen cities is shown in Fig. 1, and detailed in Table 1.

- Sapporo: Sapporo is the fourth-largest city in Japan by population, and the largest city on the northern Japanese island of Hokkaido.
- Tokyo: Tokyo is both the capital and largest city of Japan in the Kanto region on the southeastern side of the main island Honshu.
- Nagoya: Nagoya is the largest city in the Chubu region of Japan. It is Japan's third-largest incorporated city and located on the Pacific coast on central Honshu of Japan.
- Osaka: Osaka is the second largest metropolitan area in Japan and among the largest in the world with over 19 million inhabitants.
- Fukuoka: Fukuoka is the capital city of Fukuoka Prefecture and is situated on the northern shore of the island of Kyushu in Japan.
- Naha: Naha is the capital city of Okinawa Prefecture, Japan. It is a city on the west coast of Okinawa Island.

Meteorological data for the thermal load calculation is based on the weather stations located at the coordinates in Table 1.

The simulation was done for one floor of an office building with an air-conditioned area of 605 m^2 as shown in Fig. 2. It is assumed that there are no surrounding buildings and no shadows on the building. The simulation building is evaluated in Sapporo, Tokyo, Nagoya, Osaka, Fukuoka and Naha, Japan. The thermal load calculation is for a mid-level floor, not a ground floor or a roof level. Details of the simulation building and conditions of the thermal load calculation are shown in Table 2. The schedule of internal heat generation is shown in Fig. 3. The cross-sectional view of the external wall structure is shown in Fig. 4.

3. Methodology

Compared to Ozel's research [22], the methodology of this paper to optimize the combination of surface reflectivity and insulation thickness of exterior walls implemented is based on a thermal load calculation using the simulation program "New HASP/ACLD-β" which is widely used in Japan [27–29], and a cost analysis, adding the cost of surface reflective materials in the Japan market to the energy costs. The thermal load calculation is used to find the appropriate surface reflectivity for reducing annual cooling load of buildings. The economic analysis is used to predict the minimum total cost of exterior wall.

3.1. Thermal load calculation

In this research, the software "New HASP/ACLD-β" is used to calculate the thermal loads of buildings. As EnergyPlus is used in U.S., New HASP/ACLD-β is a simulation program often used to calculate the indoor temperature, humidity and thermal loads of buildings, which has been developed for the purpose of evaluating the energy consumption of air-conditioning in buildings. Parameters in New HASP/ACLD-β calculation program, such as the solar reflectivity of exterior walls, structure of building walls, operating condition of air conditioning, could be rewritten easily [30]. To calculate the thermal loads of buildings by New HASP/ACLD-β, the following input data are needed for the calculation period.

- Hourly Meteorological data: air temperature, absolute humidity, direct solar radiation, diffuse solar radiation, cloud cover, wind direction and wind speed, etc.
- Building data: the longitude, latitude of the building, wall dimensions and directions, roof and overhang dimensions, ground height, solar reflectivity of ground, solar radiation absorption and long-wave emissivity of outer walls, the structure and materials of outer and inner walls, ceiling height, distance to and height of neighboring buildings (not used here), and schedule of indoor activities and occupancy, etc.

For this analysis, the chosen input variables for the building are the surface reflectivity of exterior walls and the insulation thickness of exterior walls. The output data can be analyzed for hourly, daily, monthly and yearly thermal loads of the building.

The estimation of thermal loads of the building, including the annual cooling loads and the annual heating loads, are carried out, varying the surface reflectivity of the building exterior walls (South-facing, West-facing and East-facing walls) from 0.1 to 0.8 in steps of 0.1, and the insulation thickness of all exterior walls from 10 mm to 100 mm in steps of 10 mm.

3.2. Cost analysis

The optimum combination of surface reflectivity and insulation thickness depends on the cost of the HR or RR building envelope material and the insulating material, the cost of annual thermal loads of building, coefficient of performance (COP) of the heating and cooling systems, building envelope lifetime, etc. The annual thermal loads tend to decrease with increasing the insulation thickness or reflectivity of building envelope. The cost of the insulating material increases linearly with the insulation thickness.