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Replication Studies paper

Optimal combination of thermal resistance of insulation materials and primary fuel sources for six climate zones of Japan

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ABSTRACT

Since the East Japan great earthquake disaster in March 2011, liquefied natural gas (LNG) to replace nuclear energy has become the most-used fuel source for energy generation in Japan. Japan is implementing energy conservation policy. Building energy consumption accounts for a large proportion of the total energy consumption. To better combine the thermal insulation of external walls and fuel source utilization will play an important role in building energy conservation. This paper aims at finding the optimal combination from four different insulation materials and four different fuel sources for residences using electricity for heating and cooling in the six climate zones of Japan. The optimal thermal resistance (OTR) of insulation materials, energy cost saving per unit area of external walls and payback periods if the OTR is adopted for six climate zones are estimated via a cost analysis and degree-day (DD) method. According to the results, the optimal combination for all climate zones has been obtained by using rock wool as the insulation material and LNG as the fuel source. The energy cost saving and payback periods are 20.4 $/m^2-yr and 0.4 yrs respectively, while the OTR is 2.5 m^{2}K/W for Sapporo (in climate zone I), 14.1 $/m^2-yr and 0.5 yrs respectively, while the OTR is 2.1 m^{2}K/W for Akita (in climate zone II),11.2 $/m^2-yr and 0.6 yrs respectively, while the OTR is 1.8 m^{2}K/W for Fukushima (in climate zone III), 5.2 $/m^2-yr and 0.8 yrs respectively, while the OTR is 1.3 m^{2}K/W for Osaka (in climate zone IV), 2.5 $/m^2-yr and 1.2 yrs respectively, while the OTR is 0.9 m^{2}K/W for Kagoshima (in climate zone V), and there is no need to adopt thermal insulation for Naha (in climate zone VI).

1. Introduction

With the continuing increase of world's population and standard of living, energy consumption becomes even more of an important issue. A continuous and cheap supply of energy is desired for economic and social development [1]. The use of non-renewable energy use can cause environmental problems, global warming and reduced quality of life. One of the most effective ways of reducing this energy use is to utilize fossil fuel sources efficiently [2,3]. A study showed that the major energy end use sectors are commercial, industrial, transportation and residential, with residential the largest consumer sector in many countries [4]. The energy demands of residential buildings are high due in part to the indoor thermal comfort requirements of buildings. As an effective measure of reducing building energy use, thermal insulation technologies of building external walls are often adopted [5,6]. The thermal insulation of building external walls can decrease the heat loss or gain through the building envelopes, but at increasing cost [7]. The influence of insulation configuration on thermal loads of buildings had been detailed by many scholars. The thermal insulation of building external walls can significantly reduce the heating and cooling needs of the zone [8]. A study on performance of the heat and multilayer reflection insulators used for buildings was implemented in South Korea [9]. The result showed that the multilayer reflection insulator keeps the indoor wall surface temperature high during winter or low in summer, enhances the comfort of the building occupants and reduces thermal loads. The influence of insulation configuration on thermal loads of buildings was evaluated and a whole-building energy modeling was performed using DOE-2.1E to predict annual heating and cooling energy demand for a one-story residential building [10]. Results showed that the material configuration of the external wall can significantly affect the annual thermal performance of the whole building under different types of climate.

Design and construction with optimal insulation thickness (OIT) should be considered as a prerequisite and a top priority for energy

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Nomenclature

$(C_T)nins$	The C_T for non-insulated walls ($/m^2-yr)
$(C_T)otr$	The C_T for OTR ($/m^2-yr)
CDD_{28}	The cooling degree-days at 28 °C base dry-bulb temperature (°C-day)
C_f	The unit cost of furels ($/kg) or ($/m^3)
COP_C	The efficiency of air conditioning during cooling period [-]
COP_H	The efficiency of air conditioning during heating period [-]
C_T	The annual total cost per unit area of building external walls ($/m^2-yr)
C_{ins}	The unit insulation cost ($/m^3)
E_{cs}	The energy cost saving if the OTR is adopted ($/m^2-yr)
HDD_{18}	The heating degree-days at 18 °C base dry-bulb temperature (°C-day)
H_u	The lower calorific value of fuel sources (kJ/kg) or (kJ/m^3)
N	The period of the cost analysis (yr)
OIT	The optimal insulation thickness of external walls (m)
OTR	The optimal thermal resistance of insulation materials (m^{2}K/W)
PP	The payback period if the OTR is adopted (yr)
PWF	The present worth factor (−)
R_i	The thermal resistance of internal air film (m^{2}K/W)
R_{ins}	The thermal resistance of insulation material (m^{2}K/W)
R_o	The thermal resistance of external air film (m^{2}K/W)
R_w	The total thermal resistance of the wall layers without insulation (m^{2}K/W)
R_{wt}	The sum of R_i, R_O and R_W (m^{2}K/W)
U	The coefficient of heat transmission of external wall (W/m^{2}K)
g	The inflation rate (−)
i	The interest rate (−)
k	The thermal conductivity of insulation materials (W/mK)
m_C	The annual fuel consumption for cooling period (kg/m^2-yr)
m_H	The annual fuel consumption for heating period (kg/m^2-yr)
n	The day of heating or cooling periods (day)
q	The heat loss from unit external wall surface (W/m^2)The heat loss from unit external wall surface (W/m^2)
x	The insulation thickness (m)
ΔT	The temperature difference between indoor and outdoor sides (°C or K)
η	The electric generation efficiency for fuel sources (−)
θ_{ic}	The design indoor dry-bulb temperature for cooling period (°C)
θ_{ih}	The design indoor dry-bulb temperature for heating period (°C)
$\theta_{om(d)}$	The mean daily outdoor dry-bulb temperature of the d-th day (°C)

savings in buildings [11]. The definition of OIT has been detailed by many researchers worldwide [12,13]. A numerical model was used to determine the annual thermal transmission loads, then the calculated thermal transmission loads were inputted to an economic model to determine the OIT for a south-facing wall in the climatic conditions of Elazığ, Turkey [14]. The degree-day (DD) method is commonly used to calculate the energy needs of buildings, and methods of calculating the OIT are proposed based on the DD method and life-cycle cost analysis (LCCA) which is widely used in different fields [15–17].

Dombaycı et al. [18] have calculated the OIT of external wall for five different energy sources (coal, natural gas, LPG, fuel oil and electricity) and two different insulation materials (expanded polystyrene (EPS) and rock wool) for Denizli, Turkey. It shows that the OIT is obtained by using the coal as the primary energy source and EPS as the insulation material. In addition, a study on the determination of OIT of indoor pipelines of split air conditioning systems with consideration of four different insulation materials (EPS, rock wool, foam board and extruded polystyrene (XPS)) was also carried out using the LCCA [19]. It shows that EPS is a better choice when the OIT is an important consideration.

Japan has high electricity costs compared with other major economies, in 2013 nearly 50% higher than the OECD average unit cost. The portion of consumer spending on energy reached a record high of 8.6% as of 2014, chiefly due to electricity price increases [20]. Part of Japan's Energy Plan for FY2030 includes a focus on residential energy conservation through building and renovating houses, including improved thermal insulation and high-efficiency air-conditioners with the goal of certification as low-carbon buildings [21]. The Government of Japan aims by 2030 for all newly constructed houses to be zero energy buildings, though electricity generation will still largely depend on increasingly-efficient fossil fuel use [22].

In addition, Japan is reforming its electricity market, which had been dominated by the 10 regional Electricity Production Company (EPCOs) as near monopolies. One of the 3 stated goals of the 2013 Cabinet plan is "expanding choices for consumers and business opportunities" [23]. Retail competition for electricity distribution was expanded to the residential sector in 2016. Consumers and Energy Services Company (ESCOs) have a much greater range of options.

This paper has the goal of finding the optimum thermal resistance (OTR) of insulation materials based on the insulation cost in a residence using electricity for heating and cooling combined with the cost of the fuel source chosen by the electric utilities. Thus the OTR here is not from the viewpoint of the individual homeowner, but rather for regional or national economization goals, or for an ESCO or the new electricity retailers, trying to maximize efficiency, or minimize costs, by making recommendations to builders or remodelers concerning insulation, while also considering the primary fuel sources to aid in minimizing costs to the electric producers, which should in turn help reduce electric prices for the individual consumer and the ESCO or retailer.

The analysis is done for the six climate zones of Japan. According to the standards of energy conservation for residential and commercial building owners of Japan in 2013 [24], a total of eight climate zones were classified by considering the average heat transmission of external walls and the average rate of solar radiation gain during the cooling period as classification index. However, the eight climate zones also can be assembled into six climate zones, which includes zone I (I_a, I_b), zone II, zone III, zone IV (IV_a, IV_b), zone V, and zone VI.

For the six climate zones of Japan, the OTR of insulation materials, total energy cost saving per unit area of external walls and payback period (PP) if the OTR is adopted by different combination of four different insulation materials (EPS, rock wool, foam board and XPS) and four different fuel sources for electric power generation (coal, natural gas, LNG and fuel oil) are calculated here using a cost analysis and DD method.