A COMPARATIVE ANALYSIS OF LIFE CYCLE COST SAVINGS THROUGH OPTIMUM THERMAL INSULATION ON BUILDING WALL IN COLD CLIMATIC ZONE OF INDIA

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ABSTRACT

Acceptance of a new technology driven product generally has an issue of cost. The same issue is with vacuum insulation panel (VIP) as thermal insulation for building envelope. For acceptance of VIP while keeping its advantage of occupancy of minimum space a life cycle cost analysis is presented here with the objective to determine minimum thickness of thermal insulation for a given climatic condition on wall of building that leads to maximum savings and minimum payback period for a given period. With the said objective this paper reports results of life cycle cost analysis of building wall insulation thickness for two places in cold climatic zone of India i.e., Srinagar and Pahalgam for 40 years period. Burned brick wall common in Indian scenario is considered in the present analysis. Since the cost of VIP is high so to reduce the cost of thermal insulation another thermal insulation material, polyurethane foam (PUF) in combination with VIP is also analyzed. For the climatic condition of Srinagar in heating application it is found that for the same optimum insulation thickness of 0.005 m, combination of VIP with PUF have up to 10.35% lesser payback period with 0.453% more life cycle cost savings as compared to VIP for a life span of 40 years.

Keywords: Optimum insulation thickness; VIP; VIP-PUF combination; Life cycle cost savings.

INTRODUCTION

In order to conserve energy and corresponding cost of heating and cooling in buildings, application of thermal insulation on components of buildings in regions of extreme climates has a proven advantage at the cost of insulation (Hasan, 1999). The thickness of thermal insulation can be decided on the basis of life cycle cost analysis that leads to maximum savings or minimum total cost and that is what is known as optimum thermal insulation thickness (Ahmad, 2002;Çomakli & Yüksel, 2003). With the objectives of better efficiency of building envelope, building insulation norms across the world are now demanding higher resistance to be offered by the insulation material, it can be achieve either by increasing insulation thickness or by reducing thermal conductivity of the thermal insulation (Song & Mukhopadhyaya, 2016). In the present time vacuum insulation panel (VIP) is an advanced product in building thermal insulation market with the property of high thermal resistance, but it’s high cost is a constrain in gaining market share (Kalnæs & Jelle, 2014). This paper is an attempt to give a simple approach of combining conventional thermal insulation with VIP as a solution to the problem of high cost of thermal insulation while keeping the minimum space occupancy advantage intact from customer point of view. The

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implementation of this approach is demonstrated with its application in case of heating of building in cold climatic zone. According to the national building code (NBC) 2005 of India, cold climatic zone is one of the five major climatic zones of the country (Bhatnagar et al., 2019) which is consider for this study. The reason for selection of places of cold climatic zone of India is based on the results of earlier studies that revealed heat losses are large in buildings and thermal insulation should be employed on building envelope components like walls and roof in such places (Bhat et al., 2009; Jindal et al., 2013). For this study Srinagar and Pahalgam are considered as two places of cold climatic zone of India as both are important tourist locations (Bhat et al., 2009) and value of internal spaces in buildings worth a lot, so minimum thickness of insulation with maximum life cycle savings need to be analyze on inner portion of walls in heating application. Burned brick wall is considered in this study comprises of inner and outer plaster on brick of 230 mm thickness which is common in Indian construction practice (Jindal et al., 2013; Kumar & Suman, 2013). Heating degree day values at 18° base temperature for Srinagar and Pahalgam is based on the data of daily ambient temperature since 2003 taken from Srinagar, Rambagh centre of Indian Meteorology department (Bhat et al., 2009) to calculate annual heat losses under quasi static conditions (Cabeza et al., 2010).

LITERATURE REVIEW

The selection of thermal insulation material and its minimum thickness for achieving maximum benefits in terms of life cycle cost savings, minimum total cost and minimum environmental impacts were analyzed by number of researchers from different angles as reviewed by authors (Kaynakli, 2012; Jafri et al., 2015). Hasan (1999) analyzed optimum insulation thickness for external wall by minimizing total cost on the basis of life cycle cost analysis and determined savings over 10 years for polystyrene and Rockwool. Bolattürk (2006) analyzed optimum insulation thickness of polystyrene on the basis of minimum total cost by considering building life of 10 years. The development of any product is directly or indirectly related to the market and which is affected by the cost and services (Avesh & Srivastava, 2019, 2020; Mohd & Srivastava, 2019). With the objective of minimum occupancy of space by the insulation to fulfill the energy conservation building codes norms for U value of building envelope component for composite climate of India, different insulation materials were analyzed (Kumar & Suman, 2013). When it comes to minimum thickness of thermal insulation than VIP can be considered as an option, because of its much higher thermal resistance as compared to conventional thermal insulation materials (Simmler & Brunner, 2005; Song & Mukhopadhyaya, 2016). Alotaibi & Riffat (2014) discussed the state of art thermal insulation material VIP specially silica fumed VIP with long life and high thermal resistivity as an option for future for reducing issues related to internal spaces in heating application, although it's high cost is a hindrance in its economical acceptance. Alam et al. (2017) reported the economic viability of fumed silica VIP in high rental value nondomestic buildings for places like London on the basis of discounted payback period. Fantucci et al. (2019) justify the economical acceptance of VIP on the basis of life cycle cost analysis with the consideration of savings in space cost. Geng et al. (2021) determined optimal VIP-structural insulation panel thickness by considering aging effect of thermal insulation material by modeling the building in OpenStudio software and further using P1-P2 method for life cycle cost analysis. Gonçalves et al. (2020) also advocated the selection of VIP as candidate thermal insulation material because of its excellent thermal resistance

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properties and suggested its use in combination with other thermal insulation material for external walls composite system. Berardi and Sprengard (2020) also considered cost of VIP as an economic issue, the solution for which is required as part of future research.

On the basis of the above literature review it can be concluded that there is need to further analyze combination of VIP-PUF on building wall to see weather better life cycle cost savings can be achieve with lesser insulation cost with minimum thickness as of VIP.

METHODOLOGY

In order to analyse the optimum thermal insulation thickness on building walls as the minimum thickness at which savings should be maximum in the present research life cycle cost analysis (Al-Sallal, 2003) is used, overall heat transfer coefficient equation earlier derived for combination of thermal insulation materials (Husain Jafri & Bharti, 2018) is used in order to calculate annual heating cost through degree day method (Ucar & Balo, 2010). Further life cycle savings are determined through discounting technique, initial investment is in the form of purchasing of insulation in year zero is considered as negative saving, than the future savings of money as a difference of cost of heating without insulation and with insulation on the walls is converted into present values by considering depreciation of money, optimum value is considered as that value of thermal insulation where this life cycle saving becomes maximum. Table 1 can be referred for nomenclature used in the subsequent analysis.

TABLE 1
NOMENCLATURE USED IN THE ANALYSIS

C_{AEHS}	Annual cost of heating saved per unit area of wall (Rs/m^2)
C_{i1}	Per unit volume cost of first thermal insulation (Rs/m^3)
C_{i2}	Per unit volume cost of second thermal insulation (Rs/m^3)
C	Cost of energy per kWh (Rs/kWh)
C_t	Total cost of thermal insulation material and heating per unit area of wall (Rs/m^2)
d	Depreciation rate
F	Fraction of total thickness of thermal insulation
C_{FAEHS}	Future annual cost of heating saved per unit area of wall (Rs/m^2-year)
HDD_{18}	Heating degree day at 18° base temperature (°C-days)
HVoE	Heating value of electricity (J/kWh)
C_{TI}	Insulation cost per unit area (Rs/m^2)
k_1	Thermal conductivity of first thermal insulation (W/mK)
k_2	Thermal conductivity of second thermal insulation (W/mK)
C_{LCEHS}	Life cycle heating cost saving per unit area of wall (Rs/m^2)
C_{LCS}	Life cycle cost saving per unit area of wall (Rs/m^2)
LP	Life period (Year)

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C_{PWEHS}	Present worth of cost of heating saved (Rs/m^2)
R_{twtr}	Total wall thermal resistance without insulation (m^{2}K/W)
U_w	Without insulation overall heat transfer coefficient of wall (W/m^2-K)
U_{wwi}	With insulation overall heat transfer coefficient of wall (W/m^2-K)
x	Thermal insulation total thickness of (m)
x_o	Optimum thickness of thermal insulation
y	Variable year
DPP	Period of payback
$CPVOS_{(y_{be-1})}$	Cumulative present value of savings at the end of year just before break even
$PVoS_{y_{be}}$	Present value of saving in year of break even
η_{hs}	Heating system's efficiency

Annual cost of heating saved per unit area of the wall is determined by considering steady state heat transfer condition as given by equation (1) (Bolattürk, 2008; Husain Jafri & Bharti, 2018).

$$C_{AEHS} = 24 * 3600 * HDD_{18} * Ce * \left[\{(U_w\ ) - (U_{wwi})\} * \{\left(\frac{1}{\eta_{hs}}\right) * \left(\frac{1}{\text{HVoE}}\right)\}\right] \quad (1)$$

Where $U_w\ = 1/R_{twtr}$ and $U_{wwi} = 1/\{(R_{twtr}) + \left(F * \frac{x}{k_1}\right) + (1 - F) * x/k_2\}$ (Husain Jafri & Bharti, 2018)

Further present worth of future savings in any year y is determined by discounting method (Fantucci et al., 2019; Geng et al., 2021) by equation (2)

$$C_{PWEHS} = C_{FAEHS}/(1 + d)^y \quad (2)$$

Life cycle heating cost savings by installing thermal insulation on the walls is given by the equation (3)

$$C_{LCEHS} = \sum_{y=1}^{y=LP} C_{FAEHS}/(1 + d)^y \quad (3)$$

Life cycle cost savings per unit area of wall with the consideration of cost of thermal insulation is given by equation (4)

$$C_{LCS} = \left[\sum_{y=1}^{y=LP} C_{FAEHS}/(1 + d)^y\right] - C_{TI} \quad (4)$$

Where insulation cost per unit area of the wall for the combination of the two insulation of different fraction F is given by equation (5) (Husain Jafri & Bharti, 2018).

$$C_{TI} = C_{i1}\ * F * x + C_{i2} * (1 - F) * x \quad (5)$$

In case of without any degradation in the thermal performance of insulation i.e., considering constant thermal conductivity throughout the life period, future annual savings becomes constant and equal to C_{AEHS} so it can take out of summation sign from equation (4) and modified form of equation (4) is equation (6)

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$$C_{LCS} = \left[C_{FAEHS} \sum_{y=1}^{y=LP} \{\frac{1}{(1+d)^y}\}\right] - C_{TI} \quad (6)$$

Where $\sum_{y=1}^{y=LP} 1/(1+d)^y$ represents present worth factor, which will become constant for a given life period and depreciation rate d.

Period of payback is calculated on the basis of value of year in which first time break even achieve with the formula given by equation (7) (Geng et al., 2021) corresponding to maximum life cycle savings conditions.

$$DPP = (y_{be} - 1) + \{CPVOS_{(y_{be-1})}\}/PVoS_{y_{be}} \quad (7)$$

Calculations can be easily carried out on excel sheet for life cycle cost savings for different values of insulation thickness, the same can be represented graphically to determine optimum insulation thickness at a point where savings becomes maximum for considered unit area of the building wall.

RESULTS AND DISCUSSION

With the objective of determination of minimum thickness of thermal insulation on building walls to have maximum life cycle cost savings, life cycle cost analysis is carried out for 40 years period with the details of parameters shown in Table 2. Present cost of thermal insulation and energy is considered whereas annual depreciation rate is considered as long-term average for Indian scenario.

TABLE 2
CALCULATIONS ARE BASED ON THE FOLLOWING VALUES OF DIFFERENT PARAMETERS

Parameter	Value
HDD_{18} in °C-days for Pahalgam HDD_{18} in °C-days for Srinagar	2902.6 (Bhat et al., 2009) 1955.7 (Bhat et al., 2009)
Heating through Electricity	
C_e in Rs per kWh $HVoE$ in J/kWh η_{hs}	5.5 3600000 0.99 (Kaynakli, 2008)
Thermal insulation 1- PUF	
C_{i1} in Rs/m^3 k_1 in W/mK ρ_1(kg/m^3)	60,000 0.0251(Geng et al., 2021) 40 (Geng et al., 2021)
Thermal insulation 2- VIP	
C_{i2} in Rs/m^3 k_2 in W/mK ρ_2(kg/m^3)	485715 0.004 (Geng et al., 2021) 210 (Geng et al., 2021)
Overall heat transfer coefficient(W/m^2-K) which is reciprocal of total resistance of wall without insulation for wall type2 (230 mm burnt brick wall of thermal conductivity 0.81 W/mK with 0.0127 m plaster of thermal conductivity 0.72 W/mK on both the sides)	2.05 (Kumar & Suman, 2013)(Jindal et al., 2013)
d (%)	4

In the first part of the analysis, optimum insulation thickness of VIP is analysed on the basis of equation (6) for $F = 0$ condition. The variation of life cycle cost savings is shown in

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Figure 1 according to which life cycle cost savings initially increases at higher rate with increase of thermal insulation thickness and becomes maximum than goes down at lower rate as obvious from slope of the curve and the optimum thickness of thermal insulation is considered as one where life cycle cost savings becomes maximum (Bolattürk, 2008). These results confirm the issue of rate of diminishing returns as observed in earlier studies by increasing the thickness of thermal insulation (Al-Sallal, 2003).

Further in order to see the possibility of getting more life cycle savings and lesser payback periods with lesser investments, VIP in combination with PUF is analysed and it is found that in both the cases use of combination of VIP-PUF leads to better results as compared to VIP only with same optimum insulation thickness which can be also be seen from Figure 1.

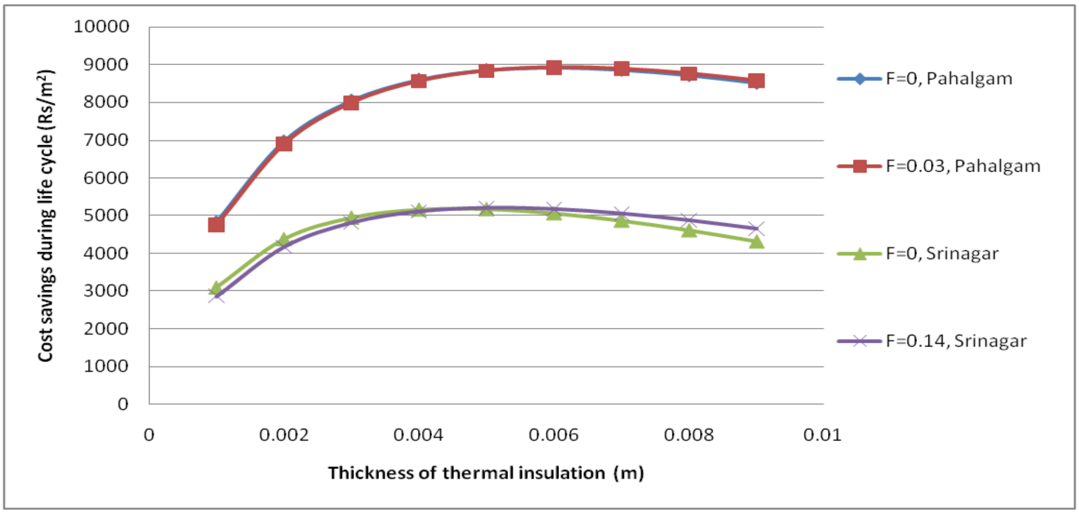

FIGURE 1

VARIATION OF LIFE CYCLE COST SAVINGS VERSUS THERMAL INSULATION THICKNESS

For Pahalgam VIP-PUF combination with 3% fraction of PUF and 97% VIP optimum insulation thickness is 0.006 m with slightly more life cycle cost savings than VIP alone for the same thickness for analysis period of 40 years and for Srinagar with optimum insulation thickness of 0.005 m even 14%PUF and 86% VIP combination leads to more savings than VIP for same thickness of 0.005 m as can be seen from Figure 1.

Such results not only lead to increase of life cycle cost savings while maintaining minimum thickness but also reduce cost of insulation as PUF is much cheaper than VIP, so investments can be getting back in lesser time period. Table 3 shows percentage increase in life cycle cost savings, percentage decrease in cost of insulation and percentage decrease in payback periods in both the cases.

Results of Table 3 indicate that percentage decrease in the cost of insulation is greater in both the cases as compared to percentage decrease in payback period. The reason for this pattern can be explain on the basis of two costs involve in the analysis i.e., insulation cost and cost of heating. While PUF replaces VIP for fraction of thickness than insulation cost decreases but heating cost increases because lower resistance is offered by PUF as compared to VIP.

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TABLE 3
ADVANTAGES OF USING VIP-PUF IN COMBINATION AS COMPARED TO VIP ALONE AS THERMAL INSULATION ON WALL

Place	Optimum insulation thickness (m)	Percentage increase in life cycle cost saving per unit area= [{(LCS with VIP+PUF) -(LCS with VIP)}/(LCS with VIP]*100	Percentage decrease in Cost of insulation= [{(Cost of VIP+PUF) - (Cost of VIP)}/ (Cost of VIP)] *100	Percentage decrease in payback period= [{(PBP for VIP) -(PBP for VIP+PUF)}/PBP for VIP] *100
Pahalgam	0.006	0.021	2.6	2.35
Srinagar	0.005	0.453	12.27	10.35

CONCLUSION

On the basis of the above life cycle cost analysis, it can be concluded that better life cycle cost savings can be achieved by using combination of VIP with PUF as thermal insulation on selected brick wall for both the places i.e., Pahalgam as well as Srinagar. For Pahalgam, combination of VIP and PUF for the optimum insulation thickness of 0.006 m leads to 2.35% lesser payback period than VIP alone.

Whereas for Srinagar, combination of VIP and PUF for the optimum insulation thickness of 0.005 m leads to 12.27% lesser cost of thermal insulation than VIP alone with better life cycle cost savings.

The results of this paper are although specific to the climatic conditions of Srinagar and Pahalgam but this must encourage researchers to analyze VIP in combination with other conventional thermal insulation materials for getting better life cycle cost savings with minimum thickness for other climatic conditions that may give boost to the market of VIP as it can be used in combination with conventional thermal insulation materials with lower investments.

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