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Research Article

Numerical Comparison of Thermal Performances of Different Insulation Materials in External Wall Model

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Abstract – In terms of heating and cooling buildings, thermal insulation is one of the most effective ways to conserve energy. The selection of the insulation material and the determination of the optimal insulation thickness are very important in terms of energy savings and providing thermal comfort conditions. In this study, the thermal behavior of wall models designed using 4 different insulation materials for an exterior wall was examined. The analysis was carried out using Ansys software for 4 different wall models with brick as building material and Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Neopor and Polyisocyanurate (PIR) as insulation materials. Wall models consist of 20 mm internal plaster, 215 mm brick, insulation material (EPS, XPS, Neopor and PIR) and 30 mm external plaster. To compare the analysis results, the insulation materials thickness was determined to be 100 mm. The temperature contours obtained for these wall models were compared to the optimal insulation thicknesses and payback periods obtained from the calculations. Additionally, costs were examined from an economic perspective. It was observed that heat loss was minimal, and temperature curves were better in the wall model created using PIR. Furthermore, an examination of optimal insulation thicknesses and payback periods revealed that PIR insulation thickness was more optimal, but despite its higher unit cost, the payback period was shorter.

Keywords – Thermal Insulation, Insulation Material, Thermal Analysis, Computational fluid Dynamics (CFD), Energy.

I. INTRODUCTION

Energy saving plans are being made to reduce energy consumption. Thermal insulation is at the top of these energy saving plans. The temperature inside is higher than the temperature outside during winter months. Thermal insulation materials come to the forefront because the heat transfer will be outside. The heat transfer amount is influenced by the structure's heat transfer coefficient. For this purpose, the building should be designed according to the heat transfer coefficient by considering the climate conditions [1]. Energy is important for all countries of the world. In our country, most of its energy needs are met from abroad due to insufficient energy resources. Therefore, energy needs are increasing even more. The importance of thermal insulation is better understood in order to reduce energy needs and minimize the negative effects of fossil fuels on the environment. Heat transfer occurs from high-temperature environments to low-temperature environments. In addition, as thermal resistance decreases, the speed of heat flow increases. Therefore, it is necessary to reduce the amount of energy spent in buildings while reducing heat losses in winter and heat gains in summer. Thermal insulation is done to reduce energy losses in buildings and to reduce energy costs . Thermal insulation helps to reduce cooling problems by preventing hot air in summer or by heating problems by preventing cold air in winter, depending on the climate conditions. Heat insulation can reduce heat losses caused by the temperature difference between the two environments. However, the initial investment costs of insulation materials are high. However, it has been determined that it prevents energy consumption and reduces energy consumption in the following years when the amortization period is considered thanks to the energy savings obtained [2-7].

Different insulation materials are used in buildings. The most commonly used materials for thermal insulation in buildings are EPS, XPS, PIR, Neopor, rock wool, and fiberglass. These applications protect the building not only from heat but also from moisture and all kinds of external factors, extending the lifespan of the building. While it is possible to completely insulate buildings, this will cause condensation inside the building. Therefore, there must be at least some heat exchange between the building and the outside environment. This is also called the building's ability to breathe. Energy savings of up to 50% to 70% can be achieved by insulating buildings against heat. Uygunoğlu et al. compared the fire resistance of gray EPS, white EPS, and XPS insulation materials coated with plaster of the same thickness. The coatings were exposed to flame for varying lengths of time. At the end of the experimental studies, it was observed that the insulation materials behind the plaster were significantly deformed depending on the duration of the flame [8]. Ertürk examined the effect of the addition of the air gap together with the insulation material on thermal insulation. He stated that he used sandwich wall as wall type and expanded polystyrene (EPS), extruded polystyrene foam (XPS) and rock wool for insulation material. When XPS was used, the optimum insulation thickness was calculated as 9.2 cm and when 4 cm air gap was added, it was determined that the optimum insulation thickness was 3.4 cm [9]. del Rio Merino investigated the physical and mechanical behavior of lightweight plasters containing mixtures of both XPS and EPS waste instead of perlite and vermiculite. To this end, they designed and experimentally examined different percentages of EPS and XPS waste. In these experiments, they examined dry density, superficial hardness, mechanical strength, and thermal behavior [10]. Liu et al. used a combined heat and moisture transfer model, which considers the effect of moisture transfer on heat transfer, to estimate annual energy consumption. They calculated the optimum insulation thicknesses for three cities in China. EPS and XPS were preferred as insulation materials in the study. As a result of the calculations, they stated that the optimum insulation thickness varies between 0.053m and 0.069m for XPS and between 0.081m and 0.105m for EPS [11]. In their study, Kumar and Suman aimed to determine the effectiveness of thermal insulation materials in buildings that provide effective energy savings while occupying a minimum footprint. They calculated and compared wall and roof cross-section combinations with different insulation thicknesses to determine the U-factor and R-value. The study found that other insulation materials, with a thickness of 50 mm for conventional roofs and walls, required higher thickness to meet the recommended values [12]. Albina et al. analyzed different types of thermal building insulation materials using Terahertz (THz) spectroscopy and imaging. First, they calculated the absorption coefficients of polymer foams and found an inversely proportional relationship with thermal conductivity. They stated that they performed non-destructive testing of the thermal insulation material's properties and structure by performing THz amplitude imaging to identify manufacturing defects and internal structures [13]. Mnasri et al. compared the hygroscopic behavior of different biobased materials to determine their hygroscopic properties. To this end, they experimentally measured the moisture buffer value (MBV) for different building material categories. They concluded that wood-cement composites still possess excellent moisture regulation compared to wood panels or fiber materials. They found that their buffer capacity was superior to 3 [g/m2.% RH], very similar to that of wood fiber panels, significantly reducing the total energy demand of the insulation [14]. Orlik-Kożdoń studied the practical, environmental and economic consequences of insulation materials on a building component used for thermal insulation in horizontal partitions and other applications [15]. Egbon and Tomlinson compared the most commonly used insulation types, XPS and EPS-PIR. They stated that EPS-insulated walls developed higher composite action than XPS-insulated walls due to the surface roughness of EPS. They also examined notched insulation using double-shear push-pull tests on 24 specimens (18 notched and 6 unnotched). Test parameters included GFRP bar diameter (9.5 and 16.0 mm), insulation type (XPS, EPS, PIR), and notch type (trapezoidal, rectangular). Their tests concluded that the surface roughness of XPS foam, combined with stress concentrations at the notches, caused cross-shear damage, but no EPS or PIR damage [16]. Makaveckas et al. stated that polyisocyanurate (PIR) foam, with its thin structure and low conductivity blowing gases, has significantly lower thermal conductivity than other thermal insulation materials, making it an increasingly popular thermal insulation material in construction and industry. They noted that they conducted aging procedures with differently prepared PIR samples in a climate chamber, and that thermal conductivity was measured using heat flux meters and hot box methods. They stated that comparing it with other insulation materials will contribute to the wider use of PIR products and a more accurate assessment of building energy performance [17]. Kalhor and Emaminejad examined traditional thermal insulation materials (EPS, XPS, PIR) for buildings based on various criteria, including heat resistance, cost, moisture and fire resistance, etc. They discussed the advantages and disadvantages of each insulation type and noted that optimizing the insulation material's quality depends on each building envelope type and system. They found that PIR is more cost-effective, while insulation is more suitable for heat resistance [18]. In this study, Zhang et al. [19] used a comprehensive analysis and optimization approach to investigate the effect of insulation layers on heat transfer processes. Using Simulink software, they investigated the multifaceted effects of insulation layer variables such as location, thickness, and material on TEG efficiency under various conditions. They also conducted a comparative analysis to evaluate the dynamic payback time between different modes. Optimizing these insulation parameters revealed that using Polyisocyanurate Foam (PIR) as the insulation material in the optimized PV-MCHP-TEG system achieved 19.32% efficiency, a 2.41% improvement compared to conventional PV-TEG systems without insulation.

A review of the literature revealed that various studies have been conducted on EPS, XPS, Neopor, and PIR as insulation materials. However, no studies have been found in the literature comparing EPS, XPS, Neopor, and PIR together. However, unlike literature, this study conducted thermal analyses for four different insulation materials. Temperature contours were obtained from thermal analyses. Heat loss calculations were also made. Following the thermal analyses, calculations for optimal insulation thickness and payback period were performed. Based on the data obtained from the study, it was determined that while PIR is more expensive than others in terms of unit cost, it is significantly superior in terms of optimal insulation thickness, payback period, and heat loss.

II. MATERIALS AND METHOD

A. External Wall Model

The most heat loss-gain occurs in the external walls of buildings. EPS, XPS, Neopor and PIR are designed for insulated wall models as insulation materials. Drawings of the designed external wall model are given in Figure 1. In this study, 4 different insulation materials were examined for this external wall model. The external wall model consists of internal plaster, brick, insulation material and external plaster, respectively.

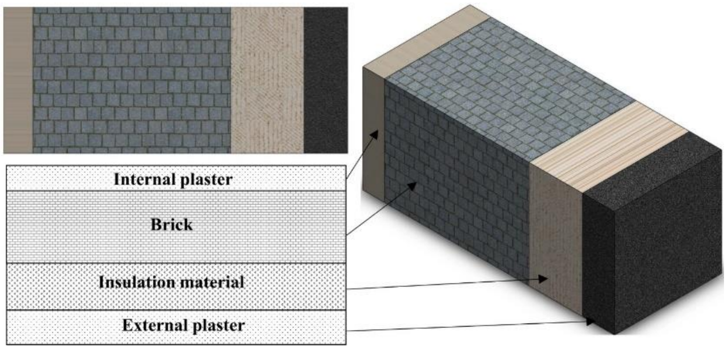

Fig. 1 Drawings of the designed the external wall model

The areas where heat loss is highest in buildings and the negative effects of the external environment are seen are usually building walls. Therefore, when choosing insulation materials, heat losses occurring on the outside of the building wall should be considered. Table 1 shows the thermophysical properties of the components for the designed exterior wall model.

Table 1. Thermophysical properties of the components for the designed exterior wall model [12-14, 20]

Wall components	**x (mm)**	**k (W/m K)**	**C_p (J/kgK)**	**ρ (kg/m³)**
External plaster	30	0.87	1000	600
Brick	215	0.39	800	1700
Internal plaster	20	1.4	1000	1300
EPS	-	0.038	1300	16
XPS	-	0.034	1351	30
Neopor	-	0.032	1450	19.8
PIR	-	0.020	1700	36

B. Numerical Modelling

Heat gains and losses in buildings generally occur because of air infiltration through exterior walls, windows, ceilings and floors. However, in this study, the optimum insulation thickness was calculated according to the heat transmission coefficient, which varies depending on the densities, considering only the heat gains and losses on the outer walls. The heat gain and loss from the unit surface of the outer wall are as follows [9, 21-22].

$$Q=U.\Delta T \quad [1]$$

Here, U is the total heat transfer coefficient ΔT, the difference between the outdoor temperature changing throughout the day and the constant indoor temperature. In this case, the annual heat gain and loss from the unit surface depending on the degree-day (DD) number [9, 21-22].

$$q_A = 86400.\mathrm{DD}.\mathrm{U} \quad [2]$$

is in the form.

The total heat transfer coefficient of the wall can be written as:

$$U= \frac{1}{Ri+R_w+R_y+R_o} \quad [3]$$

Here, R_i and R_o are the thermal resistances of the indoor and outdoor environment, and R_w is the thermal resistance of the non-insulated wall layers. R_y is the thermal resistance of the insulation material and can be written as follows.

$$R_y = \frac{x_y}{k_y} \quad [4]$$

Here, x_y, is the thickness of the insulation material, and k_y is its thermal conductivity. The total heat transfer coefficient, where R_{wt} is the total thermal resistance of the wall excluding the insulation material, is as follows [9, 21-22].

$$U = \frac{1}{R_{wt+}\frac{x_Y}{k_y}} \quad [5]$$

The heat transfer coefficient on the inner and outer surfaces of the wall was taken as 6 and 22 W/m^{2}K, respectively, and R_{wt} = 0.5903 m^{2}K/W. By applying insulation to the outer walls of the buildings, heat gain and loss are significantly reduced. In this case, it is necessary to know the optimum thickness of the insulation in terms of energy saving. The optimum thickness of the insulation is the value that provides the minimum total cost, including the cost of insulation and the cost of energy consumption over the life of the building. Therefore, the optimum insulation thickness should be determined by performing a cost analysis. The annual energy costs of heating and cooling are as follows, respectively:

$$C_{A,I} = \frac{86400.HDDC_f}{\left(R_{wt}+\frac{x_y}{k_y}\right).H_u.\eta} \qquad [6]$$

$$C_{A,S} = \frac{86400.CDD.C_e}{\left(R_{wt}+\frac{x_y}{k_y}\right).COP} \qquad [7]$$

Here HDD and CDD are the heating degree-day and cooling degree-day numbers for any region, respectively, and the Heating degree day value (HDD) and Cooling degree day value (CDD) are determined as 1344 and 116, respectively.

C_f, C_e, H_u, η and COP are the fuel price ($/kg), the price of electricity ($/kWh), the lower heating value of the fuel (J/kg), the efficiency of the heating system and the cooling performance coefficient, respectively. In this case, the total annual energy cost is written as follows.

$$C_A = C_{A,I} + C_{A,S} \qquad [8]$$

The total cost of an insulated building is calculated using the following equation.

$$C_T = C_A.PWF + C_y.x_y \qquad [9]$$

Here C_y and x_y are the price ($/m^3) and thickness of the insulation, respectively. C_A is the sum of the annual heating and cooling costs per unit surface. When determining the optimum insulation thickness, the total heating cost over N (N=10 year) -year life should be evaluated together with the present value factor (PWF). The PWF is calculated as follows depending on the interest rate (i=8,75%) and the inflation rate (g=7,5%) [7, 9].

$$PWF = \frac{(1+r)^N-1}{r.(1+r)^N}, \qquad i>g \qquad r = \frac{i-g}{1+g} \qquad [10]$$

The insulation thickness that will minimize the total cost gives us the optimum insulation thickness. Accordingly, the optimum insulation thickness is obtained by taking the derivative of the equation that gives the total cost according to the insulation thickness (x), as follows.

$$x_{opt} = 293.94\sqrt{\frac{PWF.k}{C_y}\left(\frac{C_f.IDG}{H_U.\eta} + \frac{C_e.SDG}{3{,}6.10^6.COP}\right)} - k_y.R_{wt} \qquad [11]$$

The payback period is calculated with the help of the following equation:

$$P_b = \frac{\ln\left[1-\left(\frac{i-g}{1+g}\right).\left(\frac{C_y.x_y}{S_A}\right)\right]}{\ln\left(\frac{1+g}{1+i}\right)} \qquad [12]$$

Here, SA is the annual savings and is calculated from the difference between the annual energy costs of the uninsulated wall and the insulated wall as follows [9, 21-22].

$$S_A = (C_A)_{yalsz} - C_A \qquad [13]$$

Natural gas and electricity used in the calculations price, lower calorific value (H_U) and yield values respectively 0,680 $/m^3, 34,526*10^6 J/m^3, 93%, 0,283271 $/m^3, 36,00648*10^5 J/m^3, 99%. After the mathematical calculations, analysis was started for the designed exterior wall model. A numerical mesh structure was created for the external wall model to be used in CFD (Computational Fluid Dynamics) analyses. In the analysis, the indoor and outdoor temperatures for any location were assumed to be 22 °C and -5 °C, respectively. The mesh structure of the wall model is given in Figure 2. This model has an average of 1540460 elements and 1275800 nodes [23].

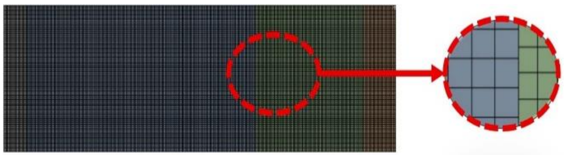

Fig. 2 Network structure of the external wall model

III. RESULTS

Insulation of buildings is an important factor affecting fuel costs and total heating costs. With increasing insulation thickness, heat loss and required energy needs decrease, while total costs also decrease. However, unnecessary and excessive insulation thickness increases insulation costs and total costs. When determining insulation thickness, the importance of optimum insulation thickness and its effect on cost should be taken into consideration. In Table 2, insulation material type, optimum insulation thickness and payback period are given.

Table 2. Insulation material and optimum parameters

Material	X optimum (m)	Payback period (Year)
EPS	0.029	4.29
XPS	0.028	3.99
Neopor	0.027	3.86
PIR	0.024	3.04

Table 2 shows the optimum insulation thicknesses for different insulation materials. As can be seen from the table, the optimum insulation thickness is 0.024 m for PIR, while it is calculated as 0.029, 0.028, and 0.027 m for EPS, XPS, and Neopor. Similarly, when natural gas is used as fuel, the payback periods are 36 months for PIR, while they are 51, 47, and 46 months for EPS, XPS, and Neopor. When four different insulation materials are compared and natural gas is used as fuel, PIR, despite its higher initial cost, yielded the best results in terms of payback time. The type of insulation should be determined depending on the usage area, lifetime, humidity, cost, and insulation thickness. When the chart above is examined, it is possible to select the type and thickness of insulation material that can provide thermal comfort conditions suitable for the desired conditions. In Figure 3, a comparison of the total costs of optimum insulation thicknesses when natural gas is used as fuel for EPS, XPS, Neopor and PIR as insulation material is given.

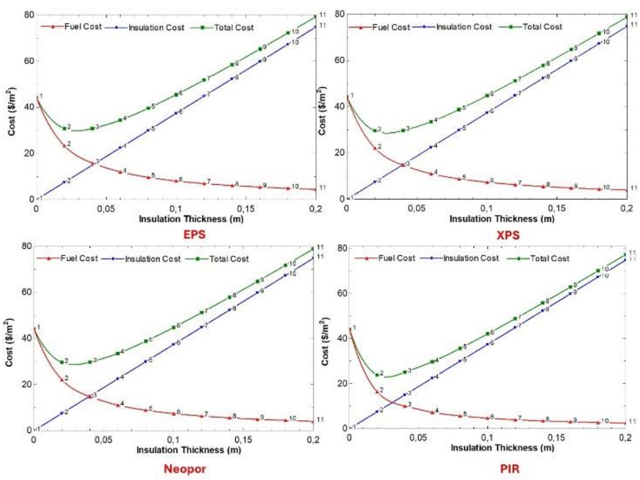

Fig. 3 Optimum insulation thickness and cost graph for the use of natural gas of different insulation materials

Figure 3 shows the relationship between insulation thickness, fuel cost, and total cost for EPS, XPS, Neopor, and PIR. As can be seen from the figure, fuel and total costs are lower for PIR, while they are higher for other insulation materials. Furthermore, it was observed that fuel costs decrease as insulation thickness increases, but total costs increase after the optimum insulation thickness is reached. In this case, using too much insulation material is not an advantage.

Figure 4 shows the changes in the temperature distribution curves along the wall in the analyses obtained after designing an exterior wall model. In order to see the temperature differences between the insulation materials in the exterior wall designs and analyses, the insulation thickness was determined as 1 m. Figure 4 shows the changes in the temperature distribution contours for the wall model according to the insulation materials.

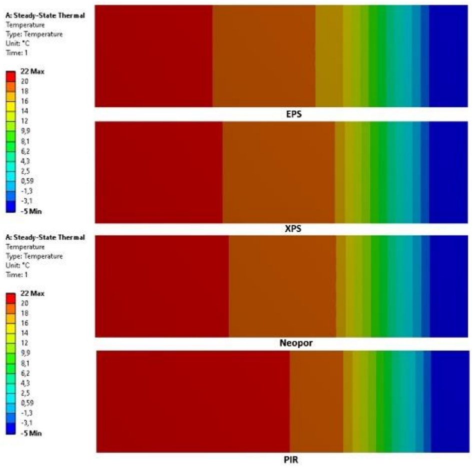

Fig. 4 Temperature contours regarding the use of natural gas in different insulation materials

When the temperature contours are examined in Figure 4, it is seen that there is a temperature difference between the exterior and interior plaster sides. When the interior temperature change is examined, it is observed that the best result is in the exterior wall model with PIR insulation material. The temperature of the insulation material with PIR insulation material is 20 °C on the interior wall side, while it is 14, 16, and 18 °C for EPS, XPS, and Neopor, respectively. While it is approximately 2 °C for the PIR wall model, the temperature difference is up to 8 °C for the EPS wall model, which is the largest among the insulation materials. When the heat losses are examined as a result of the analyses, it is observed that the lowest heat loss is in the exterior wall model with PIR insulation material and the highest heat loss is in the exterior wall model with EPS insulation material. In the calculations, the heat loss values per unit area for the EPS, XPS, Neopor, and PIR exterior wall models are found to be 9208 W/m^2, 8401 W/m^2, 7985 W/m^2, and 5306 W/m^2, respectively. Wall models consist of 20 mm internal plaster, 215 mm brick, insulation material (EPS, XPS, Neopor and PIR) and 30 mm external plaster. To compare the analysis results, the insulation materials thickness was determined to be 100 mm. The indoor and outdoor temperatures were determined for use in the Ansys software, assuming any given region. For this region, the indoor temperature was set at 22°C and the outdoor temperature was set at -5°C. In addition, 25 W/m^{2}K as the outdoor convection coefficient and 7.69 W/m^{2}K as the indoor convection coefficient were accepted. The temperature distributions of the wall were examined in the analysis. As can be seen in Figure 4, in these analyzes made according to this insulation thicknesses, it was observed that the inner wall and outer wall temperatures were close to each other.

IV. CONCLUSION

Thermal evaluations of EPS, XPS, Neopor, and PIR insulating materials were conducted in this study. Four distinct insulation materials were used to create wall models for the outer wall, and their thermal performance was examined. The wall models included insulation (EPS, XPS, Neopor, and PIR), 215 mm brick, 20 mm internal plaster, and 30 mm external plaster. To compare the analysis results, the thickness of the insulation material was fixed at 100 mm. The analysis assumed that each location's indoor temperature was 22 °C and its outdoor temperature was -5 °C. The ideal insulation thicknesses and payback durations derived from the computations contrasted with the temperature curves acquired for various wall models.

For PIR, the ideal insulation thickness is 0.024 m; for EPS, XPS, and Neopor, the corresponding values are 0.029, 0.028, and 0.027 m. In a similar vein, PIR's payback periods for natural gas fuel are 36 months, whilst EPS, XPS, and Neopor's are 51, 47, and 46 months. Despite having a higher starting cost, PIR produced the best payback period when four different insulation materials were evaluated, and natural gas was used as fuel. The utilization area, lifespan, humidity, cost, and insulation thickness should all be taken into consideration while choosing the type of insulation. The type and thickness of insulating material that can offer thermal comfort conditions appropriate for the desired conditions can be chosen by looking at the above chart.

Numerous investigations on EPS, XPS, Neopor, and PIR as insulation materials have been carried out, according to a review of the literature. Nevertheless, no research comparing EPS, XPS, Neopor, and PIR collectively has been discovered in the literature. In contrast to previous research, this study carried out thermal assessments for four distinct types of insulation. Thermal analyses were used to create temperature outlines. Calculations of heat loss were also performed. The ideal insulation thickness and payback period were calculated after the thermal evaluations. Based on the study's findings, it was concluded that PIR is substantially better than other options in terms of ideal insulation thickness, payback period, and heat loss, even if it costs more per unit. Future research on insulating materials will benefit from this. PIR insulation materials are also anticipated to grow increasingly popular and effectively.

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