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Research Article

The Numerical and Experimental Investigation of the Change of the Thermal Conductivity of Expanded Polystyrene at Different Temperatures and Densities

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The determination of the thermal conductivity of insulation materials depending on which parameters in the application as well as the production is very important. In this direction, the parameters affecting thermal conductivity should be determined to improve the efficiency of the insulation materials. It is also a fact that expanded polystyrene blocks have different thermal conductivities at the same density value depending on the production process. In this study, it was determined, experimentally and numerically, that the thermal conductivity of expanded polystyrene material at different densities is dependent on which parameters and changes in temperature. Expanded polystyrene materials consist of blocks of 30×30 cm with density of 16, 21, and 25 kg/m^3 and a thickness of 20 mm. Thermal conductivity measurements were performed in FOX 314 (Laser Comp., USA) operating in accordance with ISO 8301 and EN 12667 standards. The measurements were made for expanded polystyrene blocks at the average temperatures of 10°C, 20°C, 30°C, and 40°C. The numerical study has three stages as the acquisition of electron microscope images (SEM) of expanded polystyrene blocks, modeling of internal structure geometry with CAD program, and realization of solutions with a finite element-based ANSYS program. Findings from experimental and numerical studies and the parameters affecting thermal conductivity were determined. Finally, it is thought that numerical methods can be used to obtain a preliminary idea for EPS material in determining thermal conductivity by comparing the findings of experimental and numerical studies.

1. Introduction

The increase in the population of the world and the development of industry has increased the need for energy. This need causes the consumption of energy resources and induces heavy environmental damage. Energy should be used efficiently to decrease the environmental impact due to limited resources. Energy is consumed in different areas such as industry, transportation, agriculture, property, and other sectors. Energy consumption occurring in houses is approximately 30% in developed countries [1, 2]; therefore, decreasing energy consumption in buildings is important for both the economy and the environment. Heat insulation done for the purpose of minimizing heat loss in houses is a very important issue. Today, many features of insulation materials such as thermal conductivity, thickness, porosity, strength, sound permeability, and fire resistance are used as the evaluation criteria. Among these criteria, thermal conductivity, the main feature of insulation materials, comes to the forefront.

The thermal conductivity of the insulation materials used for houses has been determined to be, on average, 10°C according to European standards [3]. However, when climatic conditions are taken into consideration, the

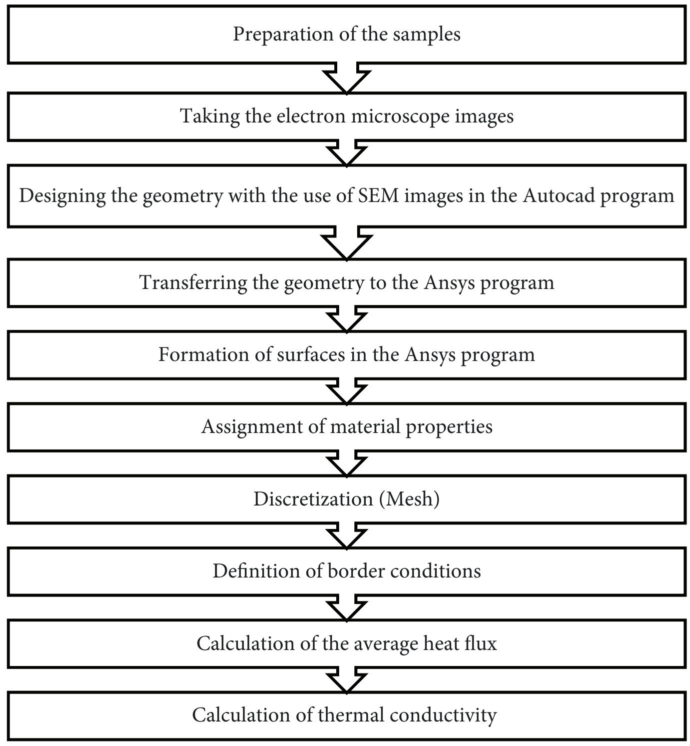


Figure 1: The flow chart for the numerical method.

average temperature interval varies between 0°C and 50°C. Investigation of the thermal conductivity of insulation materials in different temperatures is important for efficient energy use. Recently, foam insulation materials have become especially popular due to their low thermal conductivity, and they are commonly used because the production technology of expanded polystyrene is easy, production cost is low [4], the pores of the material are closed, the material is waterproof, and they have low thermal conductivity due to the air contained within them [5–10].

Thermal conductivity of a material changes depending on certain microscopic parameters: cell magnitude, the order of cells, the properties of heat radiation, and the properties of the adhesive material [11]. Also, the behavior of styrene monomer in its solid phase in relation to temperature significantly affects thermal conductivity for the expanded polystyrene material as well as the air in it [3]. The change in the thermal conductivity and the mechanical properties of the materials have been determined according to density and production parameters [12]. It has been experimentally determined that thermal conductivity decreases with an increase in density [13], and it increases or decreases with the changes in the critical thickness of the material [7, 14]. Thus, it is necessary to examine the relationship between temperature and density of the thermal conductivity of the expanded polystyrene used for the purposes of insulation in houses.

It is very important to estimate the thermal conductivity value correctly. The specific thermal conductivity measurements to be done were specified by significant researchers [6, 12]. There are many different types of insulation materials with different material structures and with different heat properties. To have correct results, a measurement method in accordance with all these criteria should be determined. The value of thermal conductivity can be determined via three different methods: experimental, numerical, and analytical. The specific method to be used depends on the type of material. In the literature, experimental methods are generally used to determine thermal conductivity for insulation materials [3, 6, 7, 11, 13, 15], but there are also a limited number of basic studies conducted by looking at the internal structure by using numerical methods as well as experimental methods [15–17].

Except for a few studies determining thermal conductivity numerically, the studies in the literature have usually been carried out experimentally. In this study, experimental and numerical methods were used and then compared to determine the thermal conductivity of expanded polystyrene material. Whether the numerical methods are valid or not was examined in detail. While conducting the numerical study, scanning electron microscope (SEM) images were examined, and the study was conducted with finite-element analysis based on the ANSYS program taking into consideration the temperature-dependent change in the thermal conductivity of the air and the polystyrene material in expanded polystyrene. The change in the thermal conductivity of the expanded polystyrene material was examined at different densities and temperatures. The parameters that affect the thermal conductivity of expanded polystyrene material were determined, and insights were gained as to what should be done to produce materials with lower thermal conductivity.

2. Material and Method

The expanded polystyrene material used for the studies was produced by the TIPOR Company (Turkey) and had a thickness of 20 mm and density of 16, 21, and 25 kg/m^3.

Samples with the dimensions of 300 × 300 × 20 mm were used in the experimental determination of the thermal conductivity of the EPS material with the average temperatures of 10°C, 20°C, 30°C, and 40°C. The samples were exposed to the drying process at 70°C in a ventilated oven to completely extract humidity before using the measurements. Mass measurements were conducted at 24-hour intervals during the drying process, and it proceeded until the difference was less than 0.2%. When the desired measurement interval was achieved, the drying process was finalized and thermal conductivity measurement processes commenced. A FOX 314 (Laser Comp., USA) device working according to the ISO 8301 standard and measuring according to the hot plate method principle was used in the experimental studies [18]. In this method, the amount of heat flux occurring as a result of the temperature difference between the hot and cold plates of the device was measured via the sensors, and the thermal conductivity was calculated with the use of Fourier's one-dimensional heat transmission equation. Five independent measurements were conducted to determine the thermal conductivity of the samples. The thermal conductivity value of the samples was calculated as the average of the five measurement values.

The application of the numerical methods used to determine the thermal conductivity of the expanded polystyrene material was conducted with the aid of the flow chart given in Figure 1. A finite element-based ANSYS 16.1 program was used to apply the numerical methods, the AutoCAD 2016 program was used in the modeling of the geometry, and the Matlab 2016 program was used in the image analysis.

The samples prepared for the modeling of the geometry were cut in the shape of a thin plate to capture images of their internal structure, and they were taped on a copper strip, the surface of which had been coated with a thin layer in the gold plating device. After the plating process, images were captured in different zoom ratios for samples with different densities in the scanning electron microscope (SEM). The attained electron microscope images were examined, the material internal structure was studied, image analyses were conducted, and a geometric model was created. The research into the pixels in the image was conducted according to the color tones in the image analyses during the geometric modeling, and the limits of the air and polystyrene material forming the expanded polystyrene material became more understandable. The geometric modeling was conducted in the AutoCAD 2016 program with the use of the images attained via image analyses. Some exceptions were made to minimize the errors in the formation of the geometry, and changes occurred in the bound sets. Thus, many models were formed, and the research for the model convenient to the study was carried out.

The transfer of the models whose geometry was formed by the ANSYS program was conducted to form the network structures and the necessary boundary conditions. The triangle elements were used for the regions formed by the air that formed the pores and the polystyrene materials out of the pores, and solutions were applied in the nodal point in appropriate numbers for the validity of the results. During the solution process, the necessary boundary conditions were defined to the right and left walls of the formed model regarding the attainment of the 10°C, 20°C, 30°C, and 40°C average temperatures as given in Figure 2. Insulation boundary conditions were given to the upper and lower walls, and

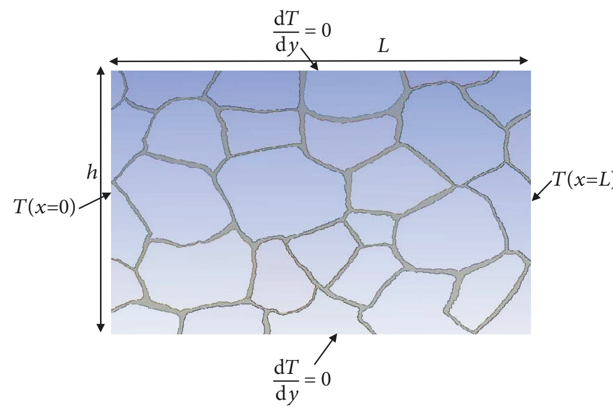


Figure 2: Boundary conditions for the numerical solution.

Table 1: Material properties for the air (1 atm) [19].

Temperature (K)	Density (kg/m^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)
278	1.269	1006	0.02401
283	1.246	1007	0.02439
288	1.225	1007	0.02476
293	1.204	1007	0.02514
298	1.184	1007	0.02551
303	1.164	1007	0.02588
308	1.145	1007	0.02625
313	1.127	1007	0.02662
318	1.109	1007	0.02699

Table 2: Material properties for polystyrene [20].

Temperature (K)	Density (kg/m^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)
240	1071	998	0.1394
260	1060	1050	0.1453
280	1051	1140	0.1507
300	1041	1230	0.1558
320	1031	1310	0.1591
340	1021	1405	0.1616
360	1011	1500	0.1629

Table 3: Experimental results for density of 16 kg/m^3.

Temperature (°C)	1. Measurement	2. Measurement	3. Measurement	4. Measurement	5. Measurement
10	0.03333	0.03323	0.03330	0.03330	0.03322
20	0.03467	0.03455	0.03463	0.03461	0.03454
30	0.03591	0.03578	0.03586	0.03585	0.03576
40	0.03711	0.03698	0.03706	0.03703	0.03696

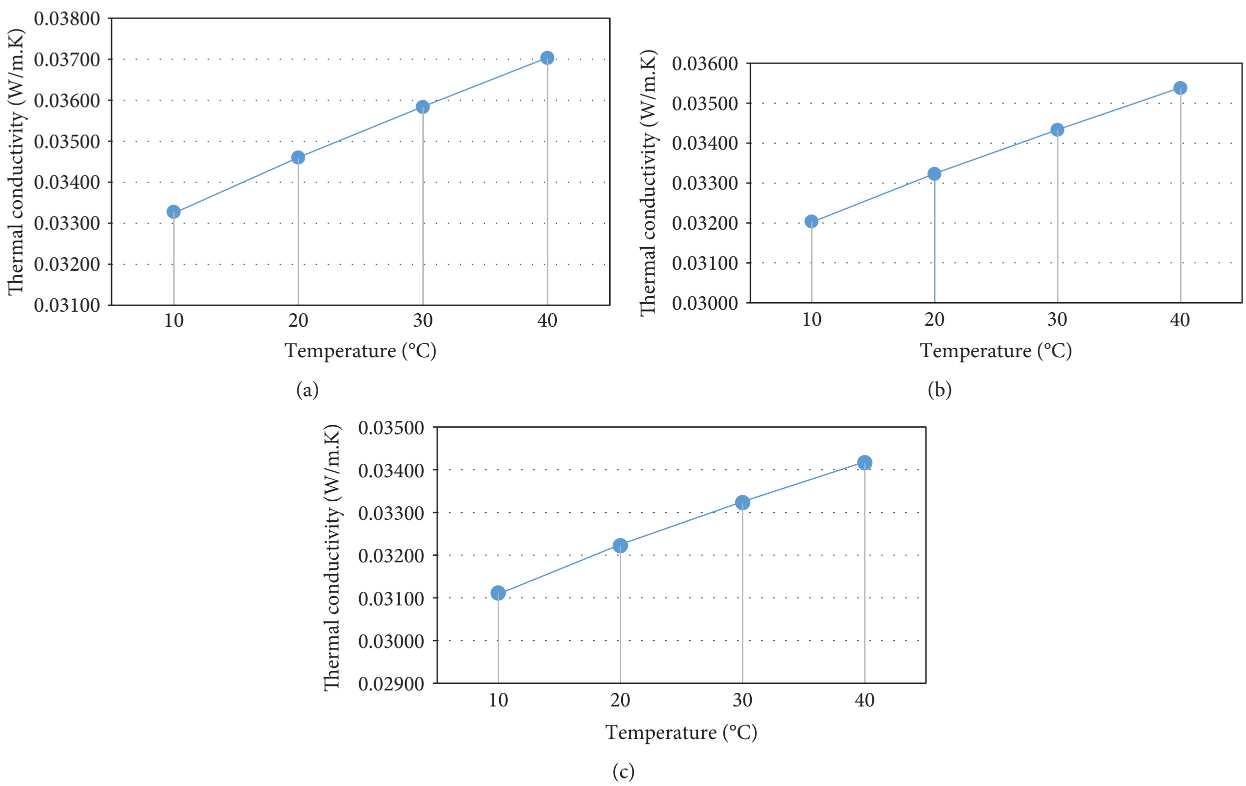


Figure 3: The change in the thermal conductivity of the expanded polystyrene with different density values with the varying temperatures (a) 16 kg/m^3, (b) 21 kg/m^3, and (c) 25 kg/m^3.

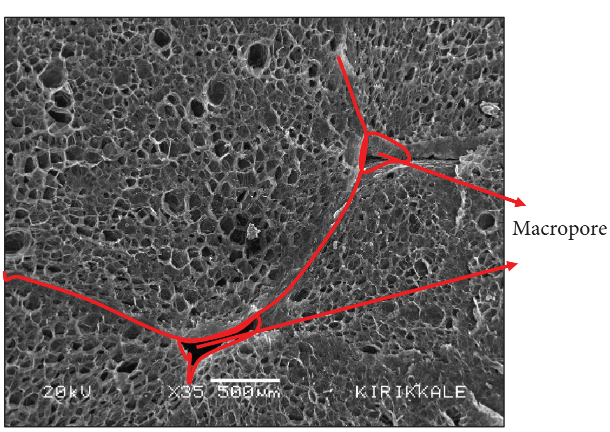


Figure 4: X35 microstructure image for the expanded polystyrene with the density of 25 kg/m^3.

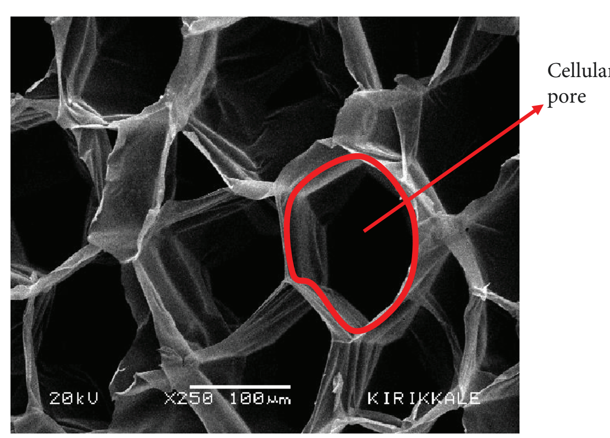
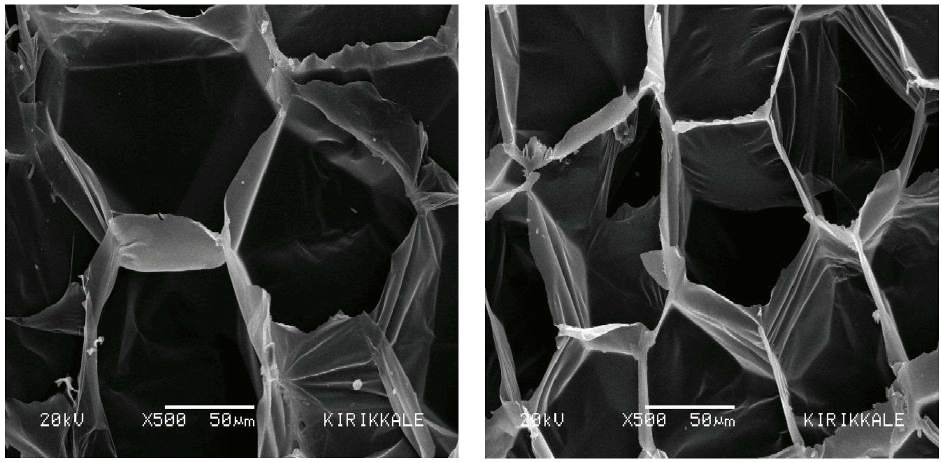


Figure 5: X250 microstructure image for the expanded polystyrene with a density value of 16 kg/m^3.



(a) (b)

Figure 6: X500 microstructure image for the expanded polystyrene: (a) 16 kg/m^3 and (b) 21 kg/m^3.

one-dimensional solutions were realized. The transport and heat transmissions are negligible in the event that the cell diameter is approximately 4 mm less [8]. As a result, neglecting the heat transfer because it is much lower with natural transport was not a mistaken acceptance in terms of the correctness of the results.

The boundary conditions are as follows:

$$\begin{aligned} &x = 0, \quad 0 \le y \le h, \quad T_{(x=0)} = T_1 = 288\,\text{K}, 298\,\text{K}, 308\,\text{K}, 318\,\text{K},\\ &x = L, \quad 0 \le y \le h, \quad T_{(x=L)} = T_2 = 278\,\text{K}, 288\,\text{K}, 298\,\text{K}, 308\,\text{K},\\ &y = 0, \quad 0 \le x \le L, \quad \left.\frac{dT}{dy}\right|_{y=0} = 0,\\ &y = h, \quad 0 \le x \le L, \quad \left.\frac{dT}{dy}\right|_{y=L} = 0. \end{aligned} \tag{1}$$

Temperature and the changing situation were taken into consideration in the definition of the material properties for the components forming the expanded polystyrene necessary during the numerical solutions. The material properties for the air and polystyrene forming the expanded polystyrene are given in Tables 1 and 2.

3. Result and Discussion

3.1. Experimental Results. The thermal conductivity value for the dried expanded polystyrene with different density values was experimentally measured for the average temperatures of 10°C, 20 °C, 30 °C, and 40°C with the use of the heat flow measurement method. The attained measurement results are given in Table 3 and Figure 3 depending on the temperature.

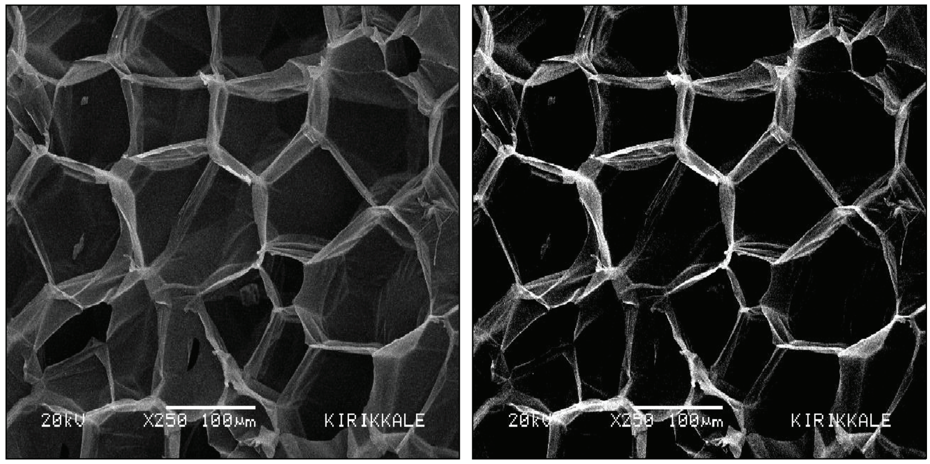
A linear distribution was observed in each density value for the expanded polystyrene depending on the temperature. As a result of this investigation, the degree of the fall or increase in this was determined with the use of the regression method. Thus, the balances expressed as a function of temperature are given in the following equations. The thermal conductivity value could be determined with an error ratio as small as 0.1% by using the balances (equations) attained by the use of the regression method.

$$\begin{aligned} k_{(16\,\text{kg/m}^3)} &= 0.032062 + 0.000125 * T,\\ k_{(21\,\text{kg/m}^3)} &= 0.030962 + 0.000111 * T,\\ k_{(25\,\text{kg/m}^3)} &= 0.030136 + 0.000102 * T. \end{aligned} \tag{2}$$

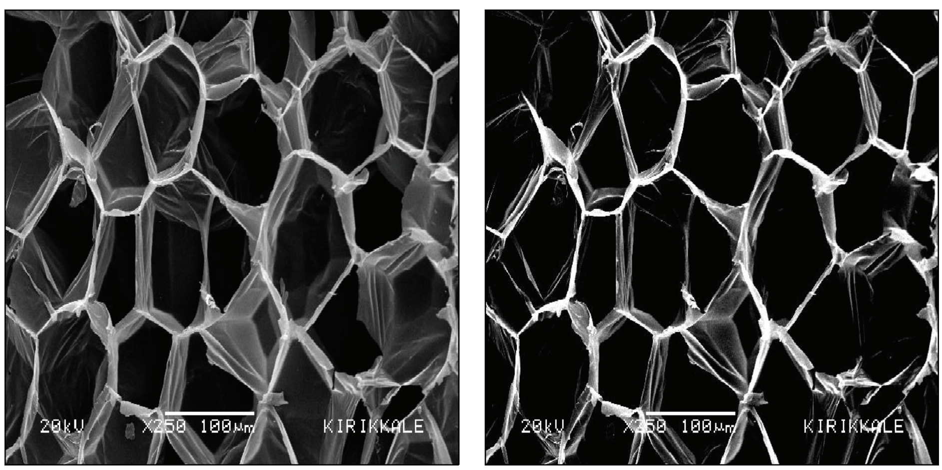
3.2. SEM Measurements. The electron microscope image given in Figure 4 was taken of the expanded polystyrene with a density of 25 kg/m^3 in a rough magnitude ratio in order to get an idea of the internal structure with regard to conducting the numerical studies.

When Figure 4 was examined, it was understood that the pore structure was not homogeneous, and it has two different pore structures for the expanded polystyrene. When the electron microscope image was taken in closer zoom ratios, in which the pore structure here is the irregular macropore, it could be observed that it has cellular pores as given in Figure 5. When the images attained as a result of scanning electron microscope (SEM) studies were examined, it was detected that the zone shown in black was the air fluid and the remaining white-looking zone was the polystyrene solid material.

It is generally known that the microlevel pore cell diameter changes between 100 and 300 μm for the expanded polystyrene and the diameters of the pores decrease with the increase in density [8, 17]. When the internal structures for the expanded polystyrene with different density values was examined, it was detected that the pore dimensions decrease because of the increase in density, as in the literature, as seen in Figure 6. Many electron microscope images were examined with 16, 21, and 25 kg/m^3 samples for the expanded polystyrene, and it was determined that the average cellular pore diameters are approximately 141 μm, 116 μm, and 95 μm, respectively.



(a)



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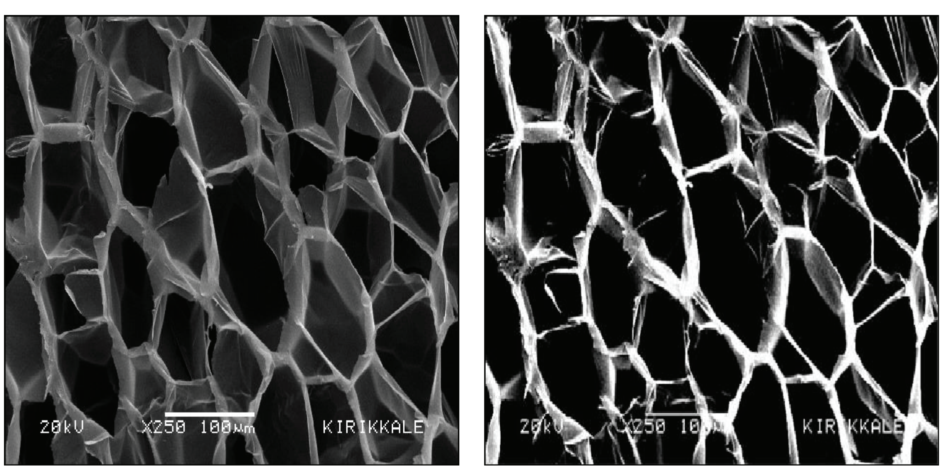

(c)

Figure 7: The electron microscope and image analysis pictures selected for the model design: (a) 16 kg/m^3, (b) 21 kg/m^3, and (c) 25 kg/m^3.

As a result of the investigations, the selection of a correct model in which the distinction of air and polystyrene is clearer was made in order to design the internal structure geometry. The selected images and the pictures attained as a result of the image processing are shown in Figure 7.

The geometry model designs were attained by using the electron microscope images that had been transferred to the ANSYS program and for whom numerical solutions were realized. During the performance of the numerical solutions, it was assumed that the heat transfer occurred only via

Table 4: The numerical solution results for the expanded polystyrene with the density value of 16 kg/m^3.

Average temperature (°C)	Average heat flux (W/m^2)	Length (m)	Temperature difference (ΔT)	Effective thermal conductivity value (W/m.K)
10	728,569	0.47E – 3	10	0.03424
20	745,446	0.47E – 3	10	0.03504
30	770,785	0.47E – 3	10	0.03623
40	800,148	0.47E – 3	10	0.03761

Table 5: The numerical solution results for the expanded polystyrene with the density value of 21 kg/m^3.

Average temperature (°C)	Average heat flux (W/m^2)	Length (m)	Temperature difference (ΔT)	Effective thermal conductivity value (W/m.K)
10	705.730	0.47E – 3	10	0.03317
20	724.935	0.47E – 3	10	0.03407
30	743.859	0.47E – 3	10	0.03496
40	759.697	0.47E – 3	10	0.03571

Table 6: The numerical solution results for the expanded polystyrene with the density value of 25 kg/m^3.

Average temperature (°C)	Average heat flux (W/m^2)	Length (m)	Temperature difference (ΔT)	Effective thermal conductivity value (W/m.K)
10	669.119	0.47E – 3	10	0.03145
20	693.253	0.47E – 3	10	0.03258
30	717.979	0.47E – 3	10	0.03375
40	733.428	0.47E – 3	10	0.03447

transmission. The thermal conductivity value was numerically found by considering it as a heat transmission problem: by determining the one-dimensional heat flow or temperature distribution and by using Fourier's heat transmission equation.

$$k_{ef} = \frac{\ddot{q}\,.L}{\Delta T}. \quad (3)$$

Here, $q^{\cdot\cdot}$ was defined as the average heat flux calculated in the ANSYS program, ΔT was defined as the temperature difference between the left and right walls of the samples, and L was defined as the length within the direction of the heat transmission.

Solutions were made for the average temperatures 10°C, 20°C, 30°C, and 40°C for the modeled geometries. The average heat flux amount transmitted as a result of the solutions was determined, and the effective thermal conductivity value was numerically calculated for each sample and temperature value via equation 3. The data attained from the numerical solutions may be found in Tables 4, 5, and 6 and Figures 8, 9, and 10. The thermal conductivity measurement data used to support the findings of this study are available from the corresponding author upon request.

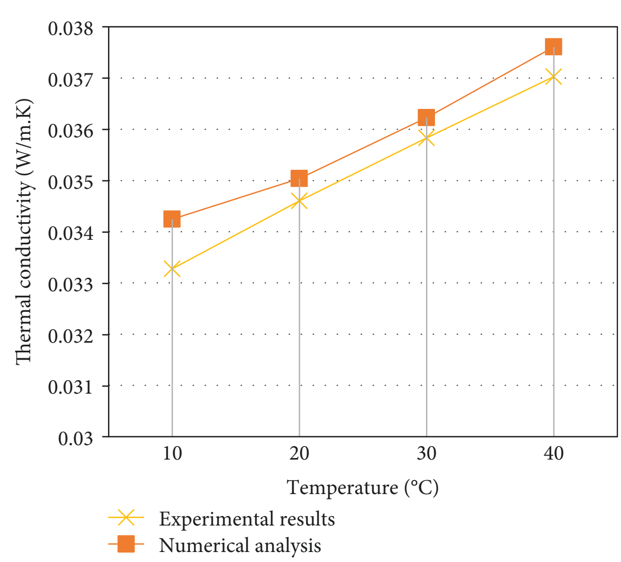

Figure 8: The comparison of the experimental and numerical results for the expanded polystyrene with the density value of 16 kg/m^3.

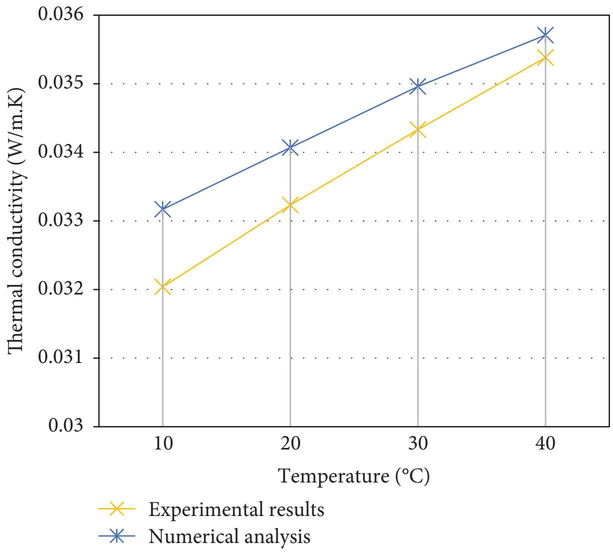

Figure 9: The comparison of the experimental and numerical results for the expanded polystyrene with the density value of 21 kg/m^3.

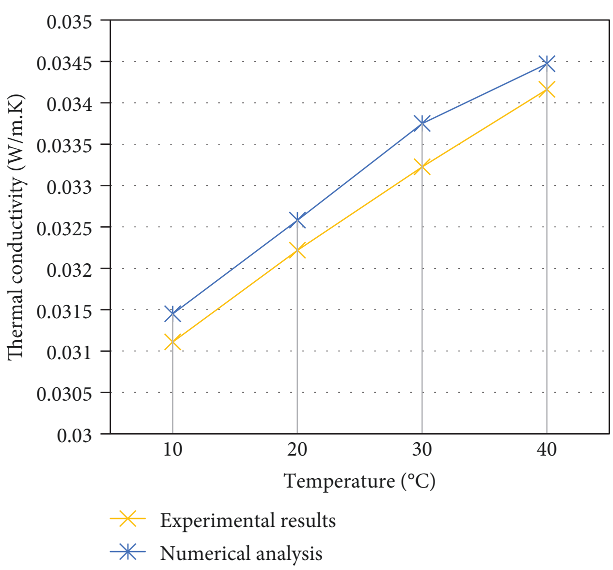

Figure 10: The comparison of the experimental and numerical results for the expanded polystyrene with the density value of 25 kg/m^3.

According to the results, the change in the thermal conductivity with density is shown in Figure 11.

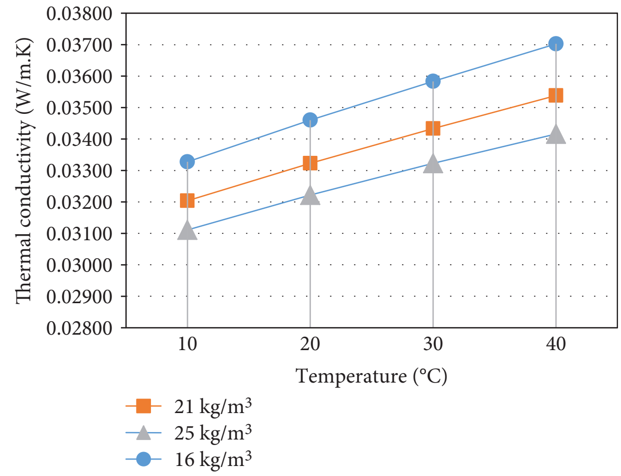

Figure 11: The change in the thermal conductivity with the temperature of the samples with different densities.

4. Conclusions

Knowing which factors the thermal conductivity value changes is a very important issue, an important parameter for the materials used to decrease energy losses. As a result of investigations, it is known that the thermal conductivity value changes depending on the distribution, dimension, and ratio of pores for the materials with a porous structure, and there are not sufficient studies regarding expanded polystyrene (EPS) material. All data generated or analyzed during this study are included in this published article.

In the internal structure images examined for expanded polystyrene with different density values, it was determined that the material components consist of polystyrene and high amount of air. As mentioned in the literature, if the porosity is examined at the macro level, the porosity rate is about 4-10% and the microporosity is known to be between 97 and 99% [17]. The reason for the different density values of expanded polystyrene is related to the amount of pores it contains.

The reason different density values occur in the study conducted on the expanded polystyrene is related to the number of pores it contains. It was detected that the number of pores decreases with the increase in the density value. In addition, the fact that the cellular pore diameters decrease with the increase in density has been supported by the electron microscope images. It is seen in results that the thermal conductivity value experimentally decreases as a result of the increase in density. Here, it is expected because of the increase in density that the number of pores decreases, and, due to this, the thermal conductivity value also increases. It can be concluded that the reason that there is a contrast between expanded polystyrene materials is that the heat transfer is realized only with conduction between two similar solid surfaces; the density increases because the transport occurring in the solid material and air boundary layers and the air speed are at very low levels, and the heat transfer with convection is at negligibly low levels as a result of the decrease in the cellular pore diameters with the increase in density.

When the results attained with the use of experimental ad numerical studies were compared, it was determined that they coincide with each other between the values 1% and 5%. The reasons for this error are from the two-dimensional structures of the numerical study, the exceptions made during the modeling, and the defined features of the component materials.

In the literature, it is seen that the thermal conductivity of the expanded polystyrenes with the same thickness and different densities is different [3, 6, 7]. When the internal structures of the different samples with different densities were examined, it was decided that the reason they have different thermal conductivities may be related to the cellular pore diameter [14]. It was determined that the thermal conductivity value for the expanded polystyrene is dependent on the cellular pore dimensions of the material, the change in the temperature and heat properties of the components, and the array of the pores, and the numerical methods can be used to obtain a preliminary idea when determining thermal conductivity.

Data Availability

The experimental data used to support the findings of this study are included within the article. The numerical data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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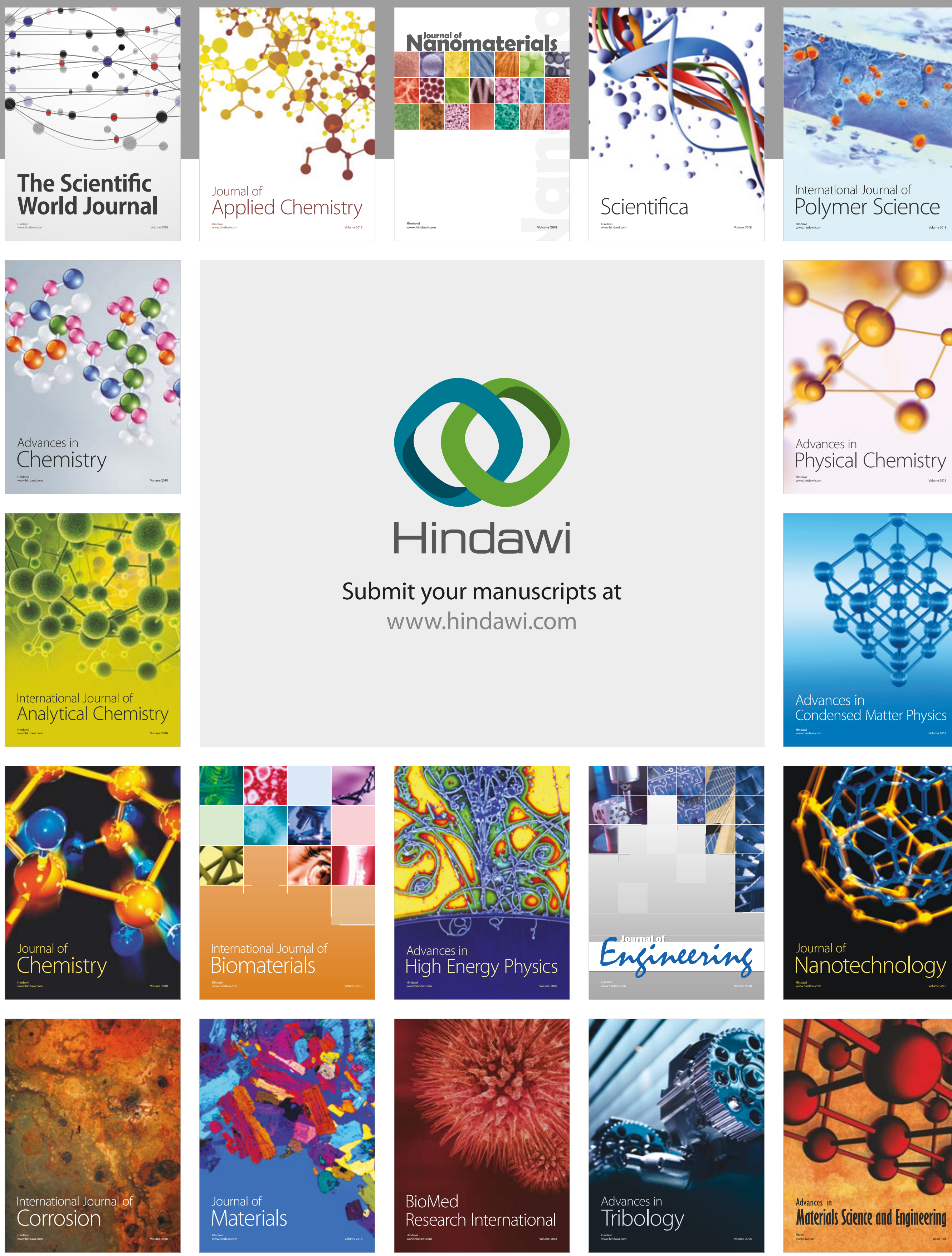
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