RESEARCH PAPER

Theoretical Investigation and Optimization of Radiation Thermal Conduction of Thermal-Insulation Polyolefin Foams

R. Hasanzadeh, S. Fathi, T. Azdast* and M. Rostami

* t.azdast@urmia.ac.ir

Received: March 2019 Revised: September 2019 Accepted: December 2019

* Mechanical Engineering Department, Faculty of Engineering, Urmia University, Urmia, Iran.

DOI: 10.22068/ijmse.17.2.58

Abstract: *Heat transfer in foams consists of conduction through solid and gaseous phases, convection within the cells as well as radiation through the whole medium. Radiation thermal conduction affects the overall thermal conductivity by 40% in a high porosity. Therefore, the investigation of that term seems to be necessary. Radiation thermal conduction depends on the extinction coefficient which its determination is experimentally complex. In this study, this coefficient is theoretically estimated using the Glicksman model for polyolefin foams and is verified in comparison with the experimental data. Extinction coefficient which plays an effective role in the radiation thermal conduction depends on the morphological properties including foam and solid densities, cell, and strut diameters. The results demonstrate that the radiation thermal conduction decreases by reducing cell size and increasing foam density and strut diameter. An L25 orthogonal array of the Taguchi approach is used for the optimization of radiation thermal conduction with respect to foam density, cell, and strut diameters as variable parameters. The analysis of variance results illuminate that foam density and cell diameter with 58 and 32% contribution are the most effective parameters on the radiation thermal conduction, respectively. At optimum conditions according to the prediction tool of the Taguchi approach, the radiation thermal conduction significantly decreases to 1.0908 mW/mK.*

Keywords: *Insulating foams, Polyolefin, Radiation, Taguchi approach.*

1. INTRODUCTION

Polymeric foams have many advantages in comparison to other thermally insulating materials such as fibrous boards [1], vacuum panels [2] and etc. They are functional materials for engineering applications. Low thermal conductivity, low cost, easy production and maintenance, and high strength to weight ratio are some advantages of polymeric foams. The low thermal conductivity of polymeric foams has many reasons such as the low void fraction of the solid polymer, low cell size which restricts the convection, the low thermal conductivity of trapped gas within the cells and etc. [3-5]. Four different mechanisms should be considered for the investigation of the thermal insulating properties of polymeric foams including conduction through the solid phase, conduction through the gaseous phase, convection within the cells, and radiation through the whole medium. It is well known that the convection term is negligible when the cell size is below 3 mm [6] due to the small cell size which prevents the movement of gas. Also, the investigation of conductions through the solid and gaseous phase is not very complicated and many experimental and theoretical studies have been performed so far. But more in-depth studies are required for investigation of radiation thermal conductivity.

Notario et al. [7] experimentally showed that reducing the cell size of polymeric foams bellow the micron decreased the gaseous thermal conductivity. They expressed that decreasing the cell size to the nanometer range significantly reduced the gaseous thermal conductivity due to the well-known Knudsen effect. Lu et al. [8] illuminated that the high expansion ratio causes higher overall thermal conductivity probably due to the more radiation contribution. Different studies showed that the conductions through gaseous and solid phases are in a relationship with the structural properties which can be measured experimentally. Therefore, the investigation of the aforementioned terms is not very challenging especially in the cell sizes above the nanometer range. But the radiation term is still facing challenges.

Placido et al. [9] studied theoretically the thermal properties of expanded and extruded polystyrene (EPS and XPS, respectively) foams. They developed morphological and prediction models for studying radiation thermal conduction. Campo-Arnaiz et al. [2] experimentally investigated the extinction coefficient of polyolefin foams. They used the Glicksman model [10] which presented for polyurethane (PU) foams. Kaemmerlen et al. [11] studied the radiation properties of XPS foams. They used the morphological model presented by Placido et al. and Glicksman's theoretical approach for the prediction of radiation thermal conduction. Their results showed that there was an acceptable difference between experimental and theoretical results.

The cells and struts are considered as pentagonal dodecahedron and cylindrical in the cell wall junctions, respectively. The schematic of morphological parameters is shown in Fig. 1.

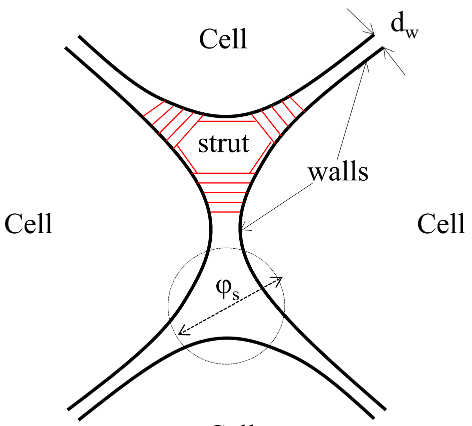


Fig. 1. The schematic of morphological parameters

The aims of this study are the investigation and optimization of the radiation behavior of polyolefin foams. Hybrid models of morphological properties and extinction coefficient presented by Placido et al. [9] and Glicksman [10] are utilized. The effects of different parameters including foam density (ρ_f), cell diameter (φ_c), and strut diameter (φ_s) are investigated on the radiation thermal conductivity. Also, the optimization of radiation behavior of polyolefin foams is performed using the Taguchi approach of the design of experiments (DOE). The optimum levels of effective parameters and the optimum response are carried out using the signal to noise ratio (S/N) analysis. The contributions of different parameters on the response variable i.e. radiation thermal conduction are obtained using analysis of variance (ANOVA).

2. RADIATION THERMAL CONDUCTION

Polymeric foams have a thickness larger than several millimeters in engineering applications. Therefore, they can be considered as optically thick materials. Hence, Rosseland equation can be applied for measuring the radiation thermal conduction (λ_r) as follows [12]:

$$\lambda_r = \frac{16n^2\sigma T^3}{3K_R} \tag{1}$$

where n is the effective index of refraction and is close to one for polymeric foams [12]. σ is Stefan-Boltzmann constant (5.67×10^{-8} W.m^{-2}.K^{-4}) and T is the mean temperature of polymeric foam. K_R is the Rosseland extinction coefficient which is a fundamental parameter in the determination of radiation conduction. This equation is reliable when the foam absorbs and scatters isotropically. Shuetz and Glicksman [13] showed that the polymeric foams can be considered as the isotropic material with a low error of about 10-15% in the radiation heat transfer calculation.

K_R is an average of spectral extinction coefficient (K_λ) based on Planck distribution of infrared radiation as follows [14]:

$$\frac{1}{K_R} = \frac{\int_0^\infty \frac{1}{K_\lambda}\frac{\partial e_{b,\lambda}}{\partial T}d\lambda}{\int_0^\infty \frac{\partial e_{b,\lambda}}{\partial T}d\lambda} = \int_0^\infty \frac{1}{K_\lambda}\frac{\partial e_{b,\lambda}}{\partial e_b}d\lambda \tag{2}$$

where $e_{b,\lambda}$ is the spectral black body emissive power, λ is the wavelength and $e_b=\sigma T^4$. $\partial e_{b,\lambda} / \partial e_b$ is calculated as follows [18]:

$$\frac{\partial e_{b,\lambda}}{\partial e_b} = \frac{\pi}{2}\frac{C_1 C_2}{\lambda^6}\frac{\sigma^{1/4}}{e_b^{5/4}}\frac{\exp\left(C_2/\lambda T\right)}{\exp\left(C_2/\lambda T\right)-1]^2} \tag{3}$$

where C_1=5.96×10^{-8} W.μm^4/m^2 and C_2=1.44×10^{-8} μm.K and are constant.

K_λ is be obtained from Beer's law as follows [15]:

$$\tau_{n,\lambda} = e^{\left(-\int_0^L K_\lambda dx\right)} \tag{4}$$

where x is the direction of heat transfer, L is the foam thickness, and $\tau_{n,\lambda}$ is the transmittance.

Transmittance can be measured for different thicknesses of polymeric foams using an infrared spectrometer and K_λ can be obtained by linear regression of ln of ($\tau_{n,\lambda}$) versus L as follows:

$$K_\lambda = \frac{-\ln(\tau_{n,\lambda})}{L} \tag{5}$$

Polyurethane (PU) foams showed approximately gray behavior at the wavelength between 5-30 microns [13]. In such cases, the average value of transmittance can be taken as $\tau_{n,\lambda}$. Shuetz and Gicksman [13] expressed that if the polymeric foam shows a dependent transmission to wavelength, spectrum should be break into a number of bands over which the transmissions are near constant and determine $\tau_{n,\lambda}$. K_λ and consequently K_R can be measured using equations (3) and (2), respectively after experimentally determination of ($\tau_{n,\lambda}$).

Glicksman et al. [16] represented a theoretical equation in order to predict the extinction coefficient (Glicksman extinction coefficient ($K_{R,G}$)) of closed-cell PU foams as equation (6). They considered the cells as pentagonal dodecahedral.

$$K_{(R,G)} = K_{struts} + K_{walls}\, K_S \tag{6}$$

where K_{struts} and K_{walls} are the extinction coefficient due to the struts and walls, respectively. K_S is the extinction coefficient of the solid polymer and for instance, Campo-Arnaiz et al. [2] measured this value for polyolefin equal to 140±20 cm^{-1}. K_{struts} and K_{walls} can be obtained as follows [11]:

$$K_{struts} = 4.10\frac{\sqrt{f_s \frac{\rho_f}{\rho_s}}}{\varphi_c} \tag{7}$$

$$K_{walls} = (1-f_s)\frac{\rho_f}{\rho_s} \tag{8}$$

where ρ_f and ρ_s are the densities of foam and polymer, respectively. φ_c is the cell diameter and f_s is the volumetric fraction of struts and can be obtained as follows:

$$f_s = \frac{V_{struts}}{V_{struts} + V_{walls}} \tag{9}$$

where V_{struts} and V_{walls} are the volumes occupied by cell struts and cell walls and can be obtained as follows, respectively [9, 12]:

$$V_{struts} = 2.8\varphi_s^2\varphi_c - 3.93\varphi_s^3 \tag{10}$$

$$V_{walls} = \frac{\rho_f}{\rho_s}0.348\varphi_c^3 - 2.8\,\varphi_s^2\varphi_c + 3.93\varphi_s^3 \tag{11}$$

where φ_s is the struts diameter. In deriving these formulas, struts and wall thicknesses are neglected with respect to cell diameter.

The wall thickness (d_w) can be obtained using the following equation [9]:

$$d_w = \frac{\frac{\rho_f}{\rho_s}0.348\varphi_c^3 - 2.8\,\varphi_s^2\varphi_c + 3.93\varphi_s^3}{1.3143\varphi_c^2 - 7.367\varphi_s\varphi_c + 10.323\varphi_s^2} \tag{12}$$

3. RESULTS AND DISCUSSION

Campo-arnaiz et al. [2] experimentally measured structural properties and the extinction coefficient for different polyolefin foams. Their results are illustrated in Table 1. Also, the predicted extinction coefficient ($K_{R,G}$) using equation (6) and the difference between experimental and theoretical results are indicated in Table 1. Table 1 shows that the theoretical error is in the range of 5-50%. Campo-araniz et al. [2] expressed that the theoretical value of the extinction coefficient ($K_{R,G}$) predicts K_R with an acceptable difference for polyolefin foams. Fig. 2 shows the difference between experimental and theoretical prediction values of extinction coefficient versus the cell diameter. The results illuminate that the difference between K_R and $K_{(R,G)}$ is more acceptable in the cell diameter greater than 400 μm. Therefore, in this theoretical study, the investigated cell diameter versus radiation thermal conductivity is above 400 μm that is in the aforementioned range.

Table 1. The experimental of polyolefin foams performed by Campo-arnaiz et al. 2] and theoretical results

Polyolefin foam		(kg.m^{-3})	(kg.m^{-3})	(μm)	(cm^{-1})	(cm^{-1})	Error (%)
1	0.24	42.6	926	674	10.5	11.3	-7.5
2	0.43	74.0	926	893	11.6	14.9	-28.3
3	0.14	34.2	920	470	15.8	10.8	31.8
4	0.23	61.6	920	616	14.6	15.5	-6.0
5	0.11	24.0	920	786	7.5	6.0	19.4
6	0.22	16.7	910	313	19.8	10.3	47.8
7	0.16	24.6	910	312	20.2	11.8	41.5
8	0.24	30.8	910	528	17.0	10.6	37.6
9	0.28	32.0	910	424	15.3	13.1	14.1
10	0.33	61.0	910	162	32.8	43.9	-33.9
11	0.31	25.5	910	255	23.8	17.7	25.7

Among the morphological parameters, measuring the cell diameter (φ_c) is easier. Also, the foam and solid densities (ρ_f and ρ_s, respectively) can be measured experimentally for instance by Archimedes principle. The expressed morphological equations in the previous section can be used for measuring other morphological parameters that cannot be obtained experimentally including cell wall thickness (d_w) and the volumetric fraction of struts (f_s).

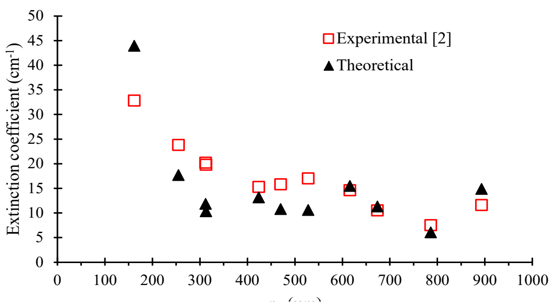
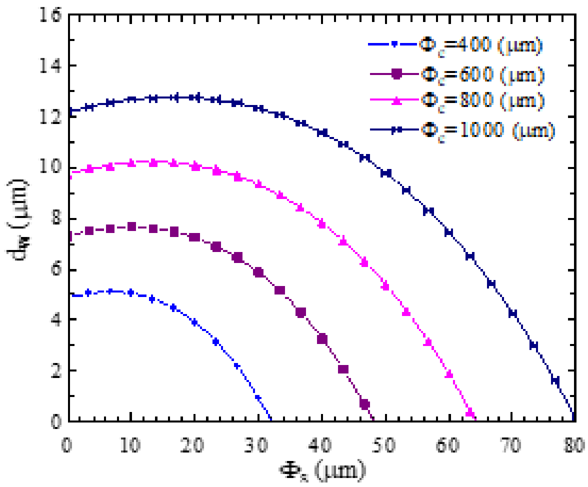
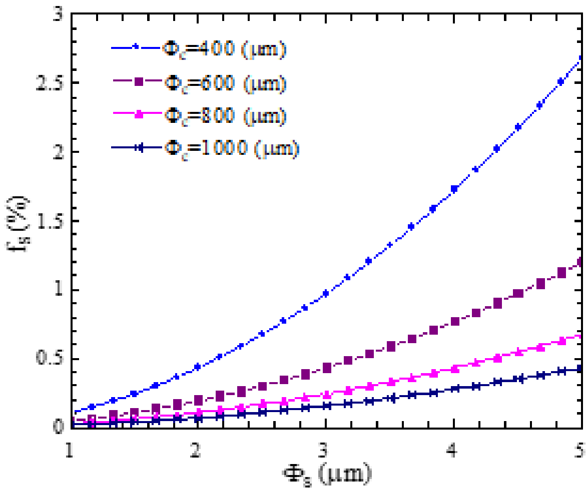


Fig. 2. The difference between experimental and theoretical extinction coefficient versus cell diameter

Fig. 3 shows the variation of d_w and f_s versus strut diameter (φ_s) at different cell diameters (φ_c). The results show that by increasing the strut diameter, the cell wall thickness and strut fraction is decreased and increased, respectively. Also, at a constant strut diameter, the cell wall thickness and strut fraction are decreased and increased, respectively by decreasing the cell diameter.



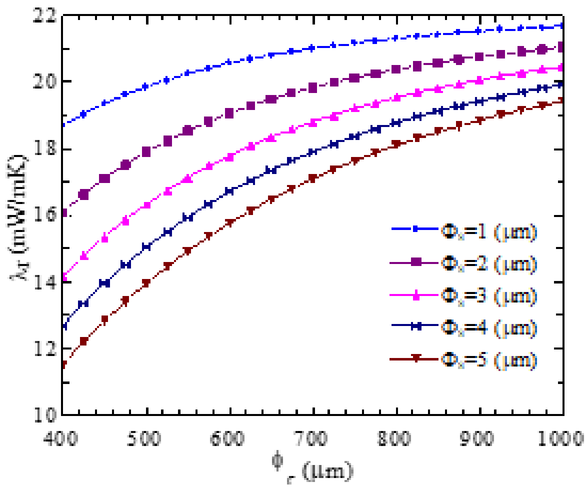
a



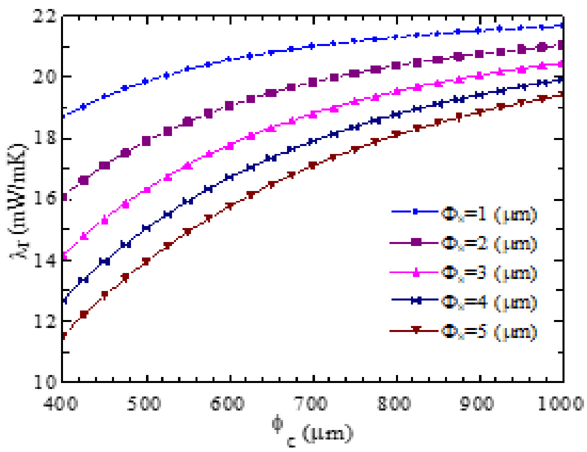
b

Fig. 3. The variation of a) d_w and b) f_s vs. φ_s at ρ_f=42.6 kg.m^{-3} and ρ_s=926 kg.m^{-3}

In the following, the effect of different structural properties on the radiation thermal conduction (λ_r) is studied. Fig. 4 shows the effect of cell size on λ_r at various strut diameters for two different foam densities. The results demonstrate that λ_r is decreased by reducing the cell size. By reducing the cell size, the number of cells and consequently the cell walls increased and more radiation is absorbed and therefore, the radiation conduction is decreased.



a

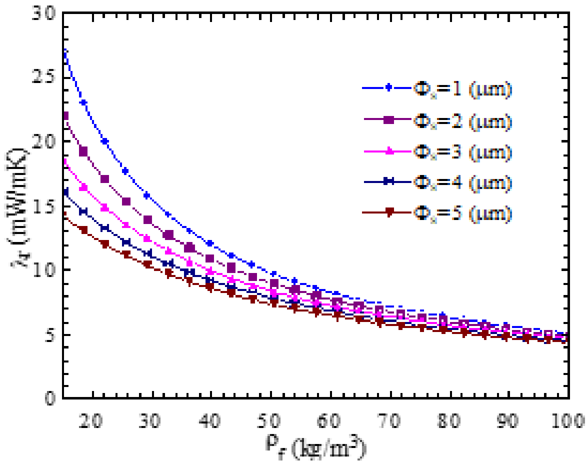


b

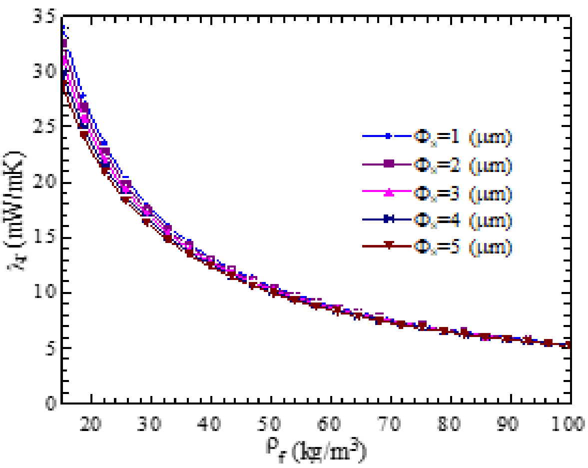
Fig. 4. The effect of cell size on radiation thermal conduction at a) ρ_f=24 kg.m^{-3} and b) ρ_f=61.6 kg.m^{-3}

The effect of foam density on λ_r is shown in Fig. 5. By reducing the foam density, λ_r is increased. In low densities, the fraction of solid is low, and therefore, lower radiation is absorbed. The results demonstrate that the strut diameter does not have a significant effect on the radiation thermal conduction in high density.

Fig. 6 indicates the influence of strut diameter on the radiation thermal conduction at various cell sizes. The results illuminate that by increasing the strut diameter, λ_r is decreased due to the more absorption by struts in higher strut diameter. According to the results, the effect of strut diameter on λ_r is more significant in the low cell size.



a



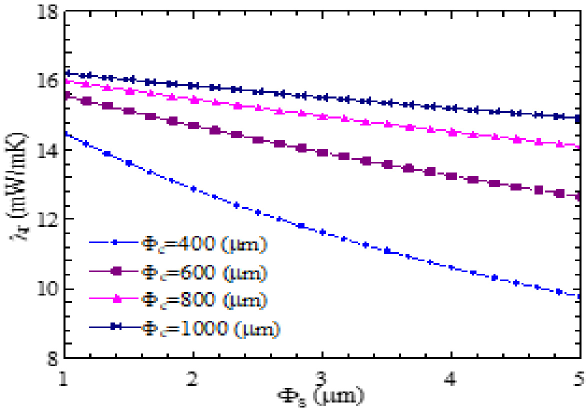
b

Fig. 5. The effect of foam density on radiation thermal conduction at a) φ_c=400 μm and b) φ_c=1000 μm

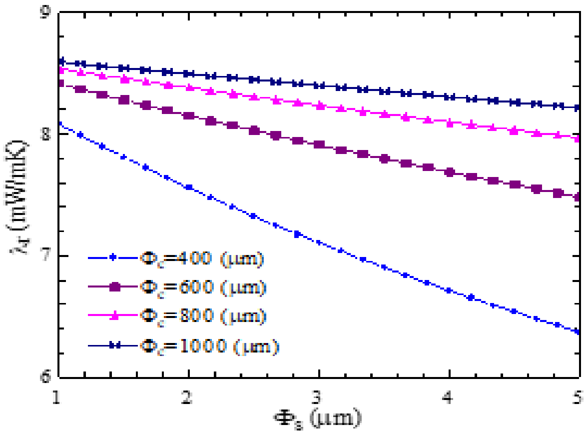
Fig. 7 shows the effect of variation of strut fraction on the radiation conduction. According to the results, increasing the strut fraction reduces λ_r at all different cell sizes.

In the following section, the optimization of radiation thermal conduction is performed using

The Taguchi approach. For this purpose, thermal radiation conduction is considered as the response variable and morphological parameters including foam density, strut diameter, and cell diameter are taken as variable parameters. Considered parameters and their levels (all at five levels) are indicated in Table 2.



a



b

Fig. 6. The effect of strut diameter on radiation thermal conduction at a) ρ_f=32 kg.m^{-3} and b) ρ_f=61 kg.m^{-3}

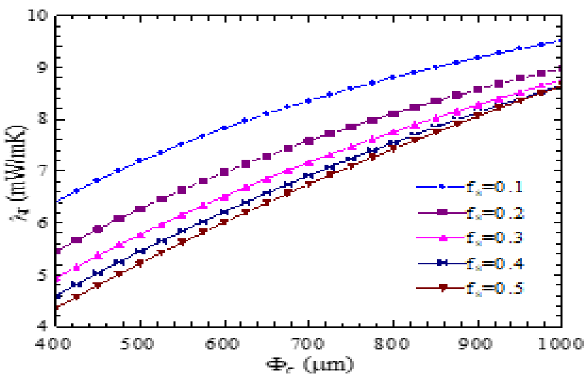


Fig. 7. The effect of strut fraction on the radiation thermal conduction

Table 2. Variable parameters and their levels

Parameter	Level				
	1	2	3	4	5
Foam density (kg/m³)	15	30	45	60	75
Strut diameter (μm)	1	2	3	4	5
Cell diameter (μm)	400	550	700	850	1000

According to the Taguchi approach, for three parameters and five levels, the design of experiments is selected based on an L_{25} orthogonal array as shown in Table 3. Also, radiation thermal conduction (λ_r) results were obtained for different trials as the right column of Table 3.

Table 3. L_{25} orthogonal array of Taguchi approach and the results

Trial	Foam density (kg.m^{-3})	Strut diameter (μm)	Cell diameter (μm)	(mW/m.K)
1	15	1	400	9.2133
2	15	2	550	9.6110
3	15	3	700	11.1085
4	15	4	850	13.0700
5	15	5	1000	15.3883
6	30	1	550	10.1004
7	30	2	700	9.6775
8	30	3	850	10.1601
9	30	4	1000	10.9418
10	30	5	400	3.4972
11	45	1	700	9.0072
12	45	2	850	8.5805
13	45	3	1000	8.6904
14	45	4	400	3.3074
15	45	5	550	4.8507
16	60	1	850	7.6425
17	60	2	1000	7.3529
18	60	3	400	3.3120
19	60	4	550	4.3819
20	60	5	700	5.3195
21	75	1	1000	6.4861
22	75	2	400	3.5150
23	75	3	550	4.1441
24	75	4	700	4.7072
25	75	5	850	5.2045

Minitab software is used for different analysis which presented in the following. The analysis of variance (ANOVA) is used for estimating the contribution of considered parameters on the response variable (λ_r). It is noteworthy that the normal distribution is the precondition to be able to apply ANOVA. Fig. 8 shows the normal probability of data in the vicinity of the diagonal line. The P-value greater than 0.05 (which is the default considered statistical error by Minitab software) delineates that the outputs follow the normal distribution.

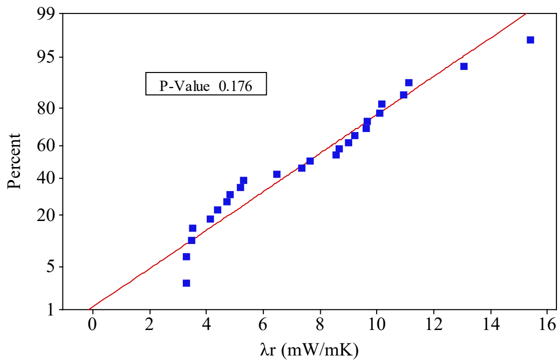


Fig. 8. The normal probability of outputs

The ANOVA results are represented in Table 4. A P-value less than 0.05 illuminate a strong overall influence on the output. The results demonstrate that all the corresponding P-values possess a value less than 0.05 except the one affiliated to the strut diameter. In other word, foam density and cell diameter with the contribution of 58 and 32%, respectively are the most significant factors on the radiation thermal conduction.

Table 4. The ANOVA results

Source	DF	SS	P	C (%)
Foam density	4	152.7	0.00	58.1
Strut diameter	4	7.4	0.37	2.8
Cell diameter	4	83.9	0.00	31.9
Error	12	18.8	-	7.2
Total	24	262.7	-	100

The optimum level of each parameter is obtained using the signal to noise (S/N) ratio analysis. These results are illuminated in Fig. 9.

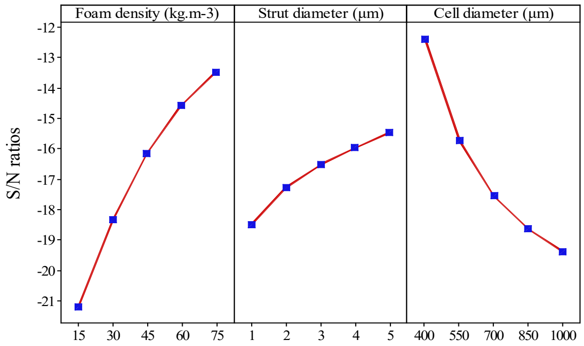


Fig. 9. The S/N ratio analysis

The level with the highest S/N ratio value is the optimum level. According to the results, the optimum levels are foam density of 75 kg.m^{-3}, strut diameter of 5 µm, and cell diameter of 400 µm. Using the prediction tool of Minitab software, the radiation thermal conduction is obtained as λ_r=1.0908 mW/mK at optimum conditions. At the optimum conditions, λ_r=2.6974 mW/mK using theoretical equations presented in the previous section.

Fig. 10 shows the interaction effect of foam density and cell diameter as the most effective parameters on the thermal radiation conduction using Minitab software.

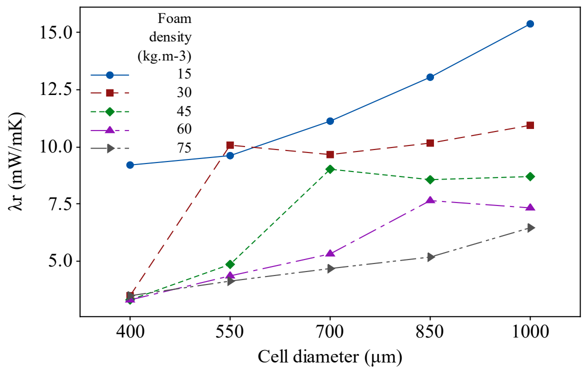


Fig. 10. Interaction of foam density and cell diameter

Fig. 10 shows that the samples with foam density of 15 kg.m^{-3} have larger λ_r in comparison to other densities almost at all cell diameters. Also, at low cell diameter, the difference between λ_r for different foam densities is negligible but this difference at high cell diameters is significant. Also, the results demonstrate that the variation of cell diameter has not effective influence on the radiation thermal conduction in high foam densities.

REFERENCES

1. Arambakam, R., Tafreshi, H. V. and Pourdeyhimi, B., "A simple simulation method for designing fibrous insulation materials". Materials & Design, 2013, 44, 99-106.
2. Campo-Arnáiz, R. A., Rodríguez-Pérez, M. A., Calvo, B. and De Saja, J. A., "Extinction coefficient of polyolefin foams". Journal of Polymer Science Part B: Polymer Physics, 2005, 43, 1608-1617.
3. Hasanzadeh, R., Azdast, T., Doniavi, A. and Lee, R. E., "Multi-objective optimization of heat transfer mechanisms of microcellular polymeric foams from thermal-insulation point of view". Thermal Science and Engineering Progress, 2019, 9, 21-29.
4. Hasanzadeh, R., Azdast, T., Doniavi, A. and Eungkee Lee, R., "Thermal-insulation performance of low density polyethylene (LDPE) foams: Comparison between two radiation thermal conductivity models". Polyolefins Journal, 2019, 6, 13-21.
5. Hasanzadeh, R., Azdast, T., Doniavi, A. and Lee R. E., "Thermal Conductivity of Low Density Polyethylene Foams Part I: Comprehensive Study of Theoretical Models". Journal of Thermal Science, 2019, 28, 1-10.
6. Hasanzadeh, R., Azdast, T., Doniavi, A. and Rostami, M., "A prediction model using response surface methodology based on cell size and foam density to predict thermal conductivity of polystyrene foams". Heat and Mass Transfer, DOI: https://doi.org/10.1007/s00231-019-02628-8.
7. Notario, B., Pinto, J., Solorzano, E., De Saja, J. A., Dumon, M. and Rodríguez-Pérez, M. A., "Experimental validation of the Knudsen effect in nanocellular polymeric foams". Polymer, 2015, 56, 57-67.
8. Lu, X., Caps, R., Fricke, J., Alviso, C. T. and Pekala, R. W., "Correlation between structure and thermal conductivity of organic aerogels". Journal of Non-Crystalline Solids, 1995, 188, 226-234.
9. Placido, E., Arduini-Schuster, M. C. and Kuhn, J., "Thermal properties predictive model for insulating foams". Infrared Physics & Technology, 2005, 46, 219-231.
10. Glicksman, L., Schuetz, M. and Sinofsky, M., "Radiation heat transfer in foam insulation". International journal of heat and mass transfer, 1987, 30, 187-197.
11. Kaemmerlen, A., Vo, C., Asllanaj, F., Jeandel, G. and Baillis, D., "Radiative properties of extruded polystyrene foams: predictive model and experimental results". Journal of Quantitative Spectroscopy and Radiative Transfer, 2010, 111, 865-877.
12. Gong, P., Buahom, P., Tran, M. P., Saniei, M., Park, C. B. and Pötschke, P., "Heat transfer in microcellular polystyrene/multi-walled carbon nanotube nanocomposite foams". Carbon, 2015, 93, 819-829.
13. Schuetz, M. A. and Glicksman, L. R., "A basic study of heat transfer through foam insulation". Journal of Cellular Plastics, 1984, 20, 114-121.
14. Mahan, J. R., "Radiation heat transfer: a statistical approach", John Wiley & Sons, 2002. 57-70.
15. Tseng, C. J., "Thermal radiative properties of phenolic foam insulation". Journal of Quantitative Spectroscopy and Radiative Transfer, 2002, 72, 349-359.
16. Glicksman, L. R., "Heat transfer and ageing of cellular foam insulation. Cellular polymers", 1991, 10, 276-293.