Predicting the Thermal Conductivity of Foam Neoprene at Elevated Ambient Pressure

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The purpose of this paper is to present a correlation for predicting the thermal conductivity of foam neoprene at varying ambient pressure. In a previous study, the authors used well-known upper and lower bounds to develop the form of a semi-empirical correlation for the thermal conductivity of foam neoprene as a function of increasing ambient pressure. The correlation was in terms of three constants, which were determined by performing a nonlinear regression on experimentally measured thermal conductivity values of foam neoprene insulation at varying ambient pressure. In this present paper, we show that the three correlation constants can, alternately, be determined by using values of the constituent thermal conductivities (e.g., air and rubber) and the effective thermal conductivity at one pressure point only (reference pressure). Values predicted using the correlation were compared with previously measured values of the effective thermal conductivity of foam neoprene insulation under increased ambient pressure, up to 1.18 MPa. It was found that there was a maximum difference of approximately 14% between the predicted and measured values. It was also found that the accuracy of the correlation did not depend strongly on the reference pressure used. It was therefore concluded that the effective thermal conductivity of foam neoprene, as a function of increasing ambient pressure, can be predicted if the constituent thermal conductivities are known (air and rubber), as well as the effective thermal conductivity at one reference pressure. [DOI: 10.1115/1.4001937]

1 Introduction

Modeling the change of the effective thermal conductivity (further referenced as k^*) of foam neoprene as a function of increasing ambient pressure is useful in predicting the performance of closed cell insulations in high pressure environments (e.g., foam neoprene used in wetsuit insulation). In order to model k^* of composite foam using theoretical correlations, the thermal conductivity of the constituents and knowledge of the shape of the gas cells needs to be known [1]. Elastomeric composite foam, such as foam neoprene, has an elastomeric rubber as a constituent. When these elastomeric closed cell composite foams are placed under increased ambient pressure, both the volume fraction of gas decreases and the shape of the gas cells change [1]. The decrease in gas volume fraction can be modeled using the ideal gas law [1], but the gas cell shape change with increased ambient pressure is not easily predicted. In addition, at atmospheric pressure, the gas cell shapes are not homogenous [1].

In a previous study by Bardy et al. [1], a semi-empirical correlation was developed for k^* of foam neoprene as a function of increasing ambient pressure, as shown in Eq. (1).

$$k^*(P) = \frac{1 + a(P/P_a)}{b + c(P/P_a)} \tag{1}$$

Equation (1) was derived from upper and lower bounds used to estimate k^* of composite foams [2–8] as a function of porosity. The upper bound, Eq. (2), is formulated assuming that the gas and rubber are arranged thermally in parallel; and, the lower bound is formulated assuming that they are arranged thermally in series, Eq. (3).

$$k^*_{\text{upper}} = k_g\phi + k_r(1-\phi) \tag{2}$$

$$k^*_{\text{lower}} = \left(\frac{\phi}{k_g} + \frac{1-\phi}{k_r}\right)^{-1} \tag{3}$$

The volume fraction of gas (ϕ) was assumed to change as a function of pressure (P) according to the ideal gas law, as shown in Eqs. (4) and (5).

$$\phi = 1 - \frac{\rho_f}{\rho_r} \tag{4}$$

where

$$\rho_f = \frac{\rho_r\left(\dfrac{P}{P_0}\right)}{\left(\dfrac{\rho_r}{\rho_0} - 1\right) + \left(\dfrac{P}{P_0}\right)} \tag{5}$$

When Eqs. (4) and (5) are substituted into Eqs. (2) and (3), they form Eqs. (6) and (7).

$$k^*_{\text{upper}} = \frac{1 + \dfrac{k_r}{k_g}\dfrac{\rho_0}{(\rho_r-\rho_0)}\left(\dfrac{P}{P_0}\right)}{\dfrac{1}{k_g} + \dfrac{\rho_0}{k_g(\rho_r-\rho_0)}\left(\dfrac{P}{P_0}\right)} \tag{6}$$

$$k^*_{\text{lower}} = \frac{1 + \dfrac{\rho_0}{\rho_r-\rho_0}\left(\dfrac{P}{P_0}\right)}{\dfrac{1}{k_g} + \dfrac{\rho_0}{k_r(\rho_r-\rho_0)}\left(\dfrac{P}{P_0}\right)} \tag{7}$$

Both Eqs. (6) and (7) are represented in the same functional form as Eq. (1). It was noted that although the individual constants (a, b, and c) in Eq. (1) are not the same as the constants in the upper and lower bounds, they yield the same asymptotic results as P approaches zero and infinity. Namely, that as P approaches 0, k^* approaches $1/b$, or k_g, and likewise, as P approaches infinity, k^* approaches a/c, or k_r. Note that k_r and k_g are typically independent of pressure variation [1]. In addition, Eq. (1) closely represents the functional form of theories used to predict k^* of composite foams that assume geometric shapes for the gas cells [1,3,5,7,8]. In the previous work by the authors, Eq. (1) was nonlinearly regressed with experimentally measured k^* values of foam neoprene at incrementally increasing pressure points to extract k_r ($=a/c$) to permit comparison of measured values to theory [1]. The results of that study showed that only experimental measurement can quantify k^* of foam neoprene at atmospheric and elevated ambient pressures due to irregular gas cell shape and variation in values for k_r.

The purpose of the presently reported investigation is to show that Eq. (1) can be put into a simple form that can be used to

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Table 1 Percent differences of k^* values determined by Eq. (8) at various pressure stops compared with measured k^* values of 5 mm and 8 mm thick foam neoprene as measured by Bardy et al. [1] using various reference pressures

	P_0(MPa)/k_0(W/m K) 5 mm thick foam neoprene					
Ambient pressure (MPa)	P_0=0.10 k_0=0.0518	0.25 0.0627	0.41 0.0735	0.56 0.081	0.72 0.0857	1.18 0.0942
0.10	0.0%	11.9%	10.9%	9.6%	9.4%	8.6%
0.25	12.6%	0.0%	1.1%	2.6%	2.8%	3.7%
0.41	9.5%	1.0%	0.0%	1.3%	1.4%	2.2%
0.56	6.8%	1.9%	1.1%	0.0%	0.1%	0.8%
0.72	5.8%	1.8%	1.1%	0.1%	0.0%	0.6%
1.18	3.6%	1.7%	1.2%	0.5%	0.4%	0.0%

	P_0(MPa)/k_0(W/m K) 12 mm thick foam neoprene					
Ambient pressure (MPa)	P_0=0.10 k_0=0.0518	0.25 0.0710	0.41 0.0860	0.56 0.0947	0.72 0.1020	1.18 0.1160
0.10	0.0%	12.3%	10.8%	11.6%	10.9%	8.4%
0.25	13.6%	0.0%	1.8%	0.9%	1.6%	4.5%
0.41	9.9%	1.5%	0.0%	0.8%	0.2%	2.3%
0.56	9.2%	0.7%	0.7%	0.0%	0.6%	2.7%
0.72	7.5%	1.1%	0.1%	0.5%	0.0%	1.9%
1.18	3.9%	2.2%	1.3%	1.7%	1.4%	0.0%

predict k^* of foam neoprene as a function of pressure if k_g and k_r are known along with k^* at only one pressure point (k_0 at P_0). The advantage of the new form is that k^* can be predicted at other pressure points independent of gas cell shape, thereby avoiding multiple experimental measurements. The validity of Eq. (1) as a model was verified by comparison to previously published experimentally measured k^* values of foam neoprene rubber as a function of increasing pressure [1,9].

2 Analysis

Equation (1) can be algebraically manipulated to be in the form shown in Eq. (8).

$$\frac{k^*(P)}{k_r} = \frac{r + R(P/P_0)}{1 + R(P/P_0)} \tag{8}$$

where

$$r = \frac{k_g}{k_r} \tag{9}$$

and

$$R = \frac{k_0 - k_g}{k_r - k_0} \tag{10}$$

Equation (8) amounts to a semi-empirical correlation as a predictive model of k^* as a function of increasing ambient pressure when k_r, k_g, and k_0 are known, and was used for direct comparison to experimental data.

The effective thermal conductivity (k^*) of foam neoprene as a function of increasing pressure has been reported in previous studies published in peer reviewed archival journals; i.e., Bardy et al. [1], Monji et al. [9], Norton and Chan [10], and West [11]. In the present paper, comparison of Eq. (2) to experimental data was limited to k^* values reported by Bardy et al. [1] and Monji et al. [9]. It is noted that the trends in their data are monotonic, as expected.

Norton and Chan [10] reported thermal conductance and compressive strain values of foam neoprene at increasing pressure stops to a pressure of 1.52 MPa (140 msw, meters of sea water) which were used to calculate k^*. These values were found to be nonmonotonic ("S" shaped) with increasing pressure and were therefore not used for comparison with Eq. (2). The reason(s) for the differences in trends are not clear; however, the nonmonotonic trends are unusual.

West [11] reported thermal conductivity, thermal conductance, and compressive strain values of foam neoprene to pressures of 0.37 MPa (27 msw). An attempt was made to regress Eq. (1) with the experimental k^* values at increasing pressure stops measured by West [11] to determine k_r; however, the resulting k_r values were anomalous when compared with other values found in the literature. Unfortunately, it was not possible to completely understand the reason for these anomalous results. It is noted, however, that the effects of the density extrema on natural convection flows in cold water [12] have not been accounted for.

Bardy et al. [1] reported the k^* values of 5 and 12 mm thick samples of foam neoprene at incremental pressure stops to 1.18 MPa (107 msw). Monji et al. [9] reported the k^* values of two 5 mm thick samples (further noted as first 5 mm thick sample and second 5 mm thick sample) and one 8 mm thick sample of foam neoprene at incremental pressure stops to 0.51 MPa (40 msw).

To compare Eq. (2) with experimental data, it was necessary to have a value of k_r, as was done by Bardy et al. [1]. Accordingly, Eq. (1) was regressed with the k^* values reported by Monji et al. [9] (assuming k_g=0.026 W/m K). The regression yielded k_r values of 0.063, 0.070, and 0.076 W/m K for the first 5 mm sample, the second 5 mm sample, and the 8 mm sample, respectively. These numbers fall slightly below the range of values found in the literature (k_r=0.100–0.192 W/m K [9,10,13–16]). The k_r values determined by Bardy et al. [1] were found to be 0.112 and 0.144 W/m K for the 5 mm and 12 mm thick samples, respectively.

In the results reported by Bardy et al. [1], a total of 9 incremental pressure stops were made (including atmospheric pressure). In this study, six of the nine pressure stops are used for comparison. Monji et al. [9] reported a total of 5 pressure stops (also including atmospheric pressure). All experimental k^* values were normalized by k_r for comparison to Eq. (2).

The value of k_0 is that of k^* measured at the reference pressure. Once k_0 was determined, Eq. (2) was used to predict $k^*(P)/k_r$ for all remaining pressure stops. Equation (2) was compared with experimental data at each pressure stop for each data set.

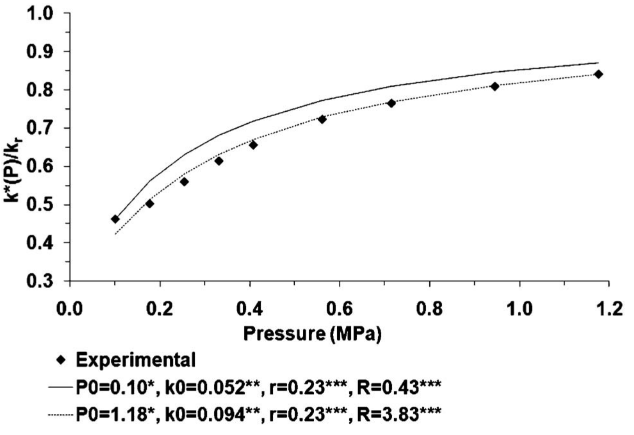

Fig. 1 Experimentally measured k^{*} values of 5 mm thick foam neoprene from Bardy et al. [1] compared with predictions of k^{*} from Eq. (8) (*MPa, **W/m K, ***unitless)

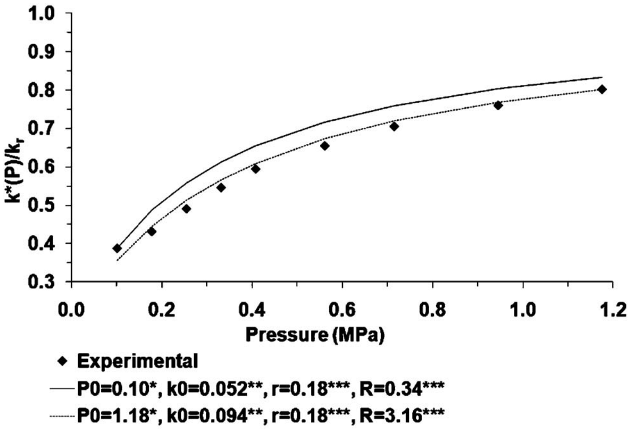

Fig. 2 Experimentally measured k^{*} values of 12 mm thick foam neoprene from Bardy, et al. [1] compared with predictions of k^{*} from Eq. (8) (*MPa, **W/m K, ***unitless)

3 Results and Discussion

Table 1 shows the percent difference between k^{*} values determined by Eq. (8) compared with experimentally measured values at six pressure stops (six different values for k_0) by Bardy et al. [1]. As can been seen, there was less than a 14% difference between values of k^{*} determined by Eq. (8) and experimentally measured values to pressures of 1.18 MPa (107 msw). The largest difference in predicted and measured values occurs when k_0 was chosen at atmospheric pressure. Figures 1 and 2 show a plot of $k^{*}(P)/k_r$ measured by Bardy et al. [1] compared with the values predicted from Eq. (8) using k_0 at a pressure of 0.10 MPa and 1.18 MPa for 5 mm and 12 mm thick foam neoprene, respectively. As can be seen, when k_0 was selected at atmospheric pressure (P_0 $=0.10$ MPa) all predicted $k^{*}(P)/k_r$ values were somewhat higher than the measured values. The percent differences were approximately 12.6% and 13.6% for 5 mm and 12 mm thick foam neoprene, respectively, at 0.25 MPa. As pressure increased, the difference between the measured and predicted k^{*} values decreased to 3.6% and 3.9% for 5 mm and 12 mm foam neoprene, respectively, at 1.18 MPa. Likewise when k_0 was selected at $P_0 > 0.10$ MPa, all the predicted values of k^{*} for $P_0 > 0.10$ MPa were less than 5% different than measured values for both the 5 mm and 12 mm thick foam neoprene. The percent differences at atmospheric pressure (for k_0 selected at $P_0 > 0.10$ MPa) were between 8% and 12%.

Table 2 shows the percent difference between k^{*} values deter-

Table 2 Percent differences of k^{*} values determined by Eq. (8) at various pressure stops compared with measured k^{*} values of 5 mm and 8 mm thick foam neoprene as measured by Monji, et al. [9] using various reference pressures

	P_0(MPa)/k_0(W/m K) 8 mm thick foam neoprene				
Ambient pressure (MPa)	$P_0=0.10$ $k_0=0.048$	0.20 0.051	0.30 0.053	0.41 0.058	0.51 0.059
0.10	0.0%	7.6%	8.8%	0.2%	2.6%
0.20	6.1%	0.0%	1.0%	6.2%	8.0%
0.30	5.5%	0.8%	0.0%	5.6%	7.0%
0.41	0.1%	3.7%	4.4%	0.0%	1.0%
0.51	0.9%	4.0%	4.5%	0.8%	0.0%
	P_0(MPa)/k_0(W/m K) first 5 mm thick foam neoprene				
Ambient pressure (MPa)	$P_0=0.10$ $k_0=0.051$	0.20 0.055	0.30 0.059	0.41 0.063	0.51 0.064
0.10	0.0%	7.7%	5.7%	0.5%	0.0%
0.20	6.1%	0.0%	1.7%	6.5%	6.1%
0.30	3.4%	1.3%	0.0%	3.6%	3.4%
0.41	0.2%	3.9%	2.9%	0.0%	0.2%
0.51	0.0%	3.1%	2.2%	0.2%	0.0%
	P_0(MPa)/k_0(W/m K) second 5 mm thick foam neoprene				
Ambient pressure (MPa)	$P_0=0.10$ $k_0=0.053$	0.20 0.059	0.30 0.063	0.41 0.067	0.51 0.069
0.10	0.0%	4.5%	4.9%	0.2%	0.6%
0.20	3.4%	0.0%	0.4%	3.6%	3.9%
0.30	3.0%	0.3%	0.0%	3.1%	3.3%
0.41	0.1%	2.2%	2.5%	0.0%	0.2%
0.51	0.2%	2.0%	2.2%	0.1%	0.0%

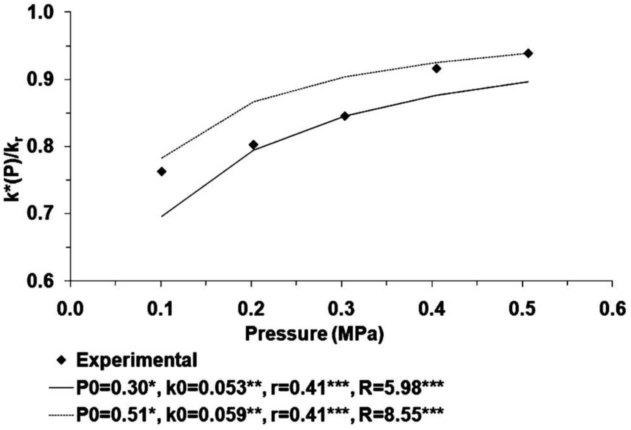

Fig. 3 Experimentally measured k^* values of 8 mm thick foam neoprene from Monji, et al. [9] compared with predictions of k^* from Eq. (8) (*MPa, **W/m K, ***unitless)

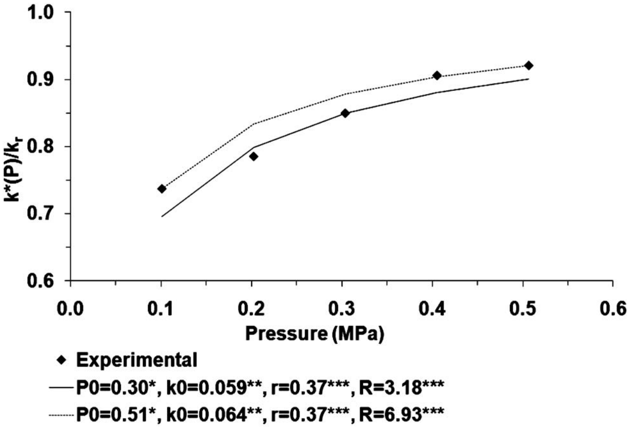

Fig. 4 Experimentally measured k^* values of the first 5 mm thick foam neoprene from Monji et al. [9] compared with predictions of k^* from Eq. (8) (*MPa, **W/m K, ***unitless)

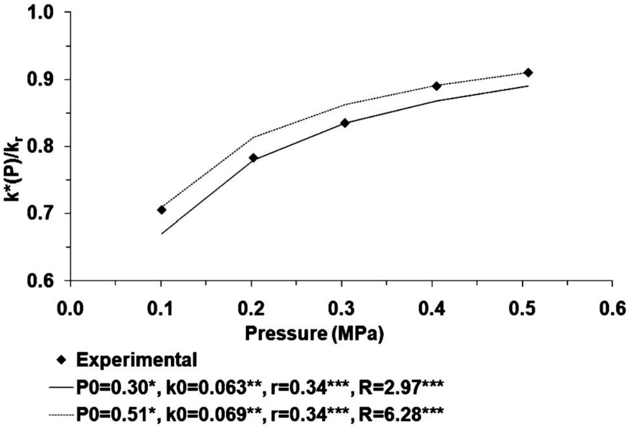

Fig. 5 Experimentally measured k^* values of the second 5 mm thick foam neoprene from Monji et al. [9] compared with predictions of k^* from Eq. (8) (*MPa, **W/m K, ***unitless)

mined by Eq. (8) compared with experimentally measured values of one sample of 8 mm thick and two samples of 5 mm thick foam neoprene at various pressure stops by Monji et al. [9]. There were a total of five reference pressures (five values of k_0). There was less than a 9% difference between experimentally measured values of k^* and values predicted from Eq. (8) for pressures up to 0.51 MPa (40 msw). The highest percent differences occur when the k_0 was chosen at $P_0=0.20$ and 0.30 MPa for the 8 mm thick sample, and when k_0 was chosen at $P_0=0.20$ MPa for the first 5 mm thick sample. Figures 3–5 show the plots of $k^*(P)/k_r$ values measured by Monji et al. [9] compared with values predicted from Eq. (8) using k_0 at a pressure of 0.30 MPa and 0.51 MPa for 8 mm and two samples of 5 mm thick foam neoprene, respectively. The deviation from the predicted values shown in Table 2 can be seen in Fig. 3 (k^* at 0.20 MPa and 0.30 MPa for the 8 mm thick sample) and Fig. 4 (k^* at 0.2 MPa for the first 5 mm thick sample). Figure 5 shows the deviations from the predicted values of less than 4% for the second 5 mm thick sample. Although there were slight deviations from the predicted k^* values present for all foam neoprene samples, they were not significant.

4 Conclusions

A semi-empirical correlation was presented to theoretically predict k^* of foam neoprene, independent of gas cell shape, as a function of increasing ambient pressure. The advantage of this correlation is that it allows the prediction of k^* of foam neoprene with increasing ambient pressure, thereby drastically minimizing the extent of required experimental measurement. Use of the semi-empirical correlation requires values for the thermal conductivity of the pure rubber constituent (k_r), the thermal conductivity of the gas constituent (k_g), and the k^* at one reference pressure (k_0 at P_0). With these three values known, k^* can be predicted for pressures above and below P_0. The predicted k^* values were shown to be within 14% when compared with experimentally measured k^* from Bardy et al. [1] and within 9% when compared with Monji et al. [9]. Therefore, it is concluded that if k_r and k_g of foam neoprene are known, as well as k^* at one pressure point (k_0 at P_0), then k^* can be predicted at ambient pressures greater and less than P_0 with reasonable accuracy. A natural extension of this work would be to investigate its applicability to other kinds of elastomeric foams.

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Nomenclature

R = constant for equation (1) $=(k_0-k_g)/(k_r-k_0)$
P_0 = reference ambient pressure
P_a = atmospheric pressure
P = ambient pressure
a = constant for Eq. (1)
b = constant for Eq. (1)
c = constant for Eq. (1)
r = ratio of thermal conductivity of gas to neoprene rubber
k_{lower} = lower bound thermal conductivity
k_{upper} = upper bound thermal conductivity
k_g = thermal conductivity of gas
k_r = thermal conductivity of neoprene rubber
k_0 = reference effective thermal conductivity
k^* = effective thermal conductivity
ρ_f = density of foam neoprene
ρ_r = density of neoprene rubber
ρ_0 = density of foam neoprene at reference pressure P_0
ϕ = volume fraction of gas in foam neoprene

References

[1] Bardy, E., Mollendorf, J., and Pendergast, D., 2005, "Thermal Conductivity and Compressive Strain of Foam Neoprene Insulation Under Hydrostatic Pressure," J. Phys. D: Appl. Phys., **38**(20), pp. 3832–3840.

[2] Brailsford, A., and Major, K., 1964, "The Thermal Conductivity of Aggregates of Several Phases, Including Porous Materials," Br. J. Appl. Phys., **15**, pp. 313–319.

[3] Calmidi, R., and Mahajan, V., 1999, "The Effective Thermal Conductivity of High Porosity Fibrous Metal Foams," ASME J. Heat Transfer, **121**, pp. 466–471.

[4] Carson, J. K., Lovatt, S. J., Tanner, D. J., and Cleland, A. C., 2005, "Thermal Conductivity Bounds for Isotropic, Porous Materials," Int. J. Heat Mass Transfer, **48**, pp. 2150–2158.

[5] Leach, A., 1993, "The Thermal Conductivity of Foams. I: Models for Heat Conduction," J. Phys. D: Appl. Phys., **26**, pp. 733–739.

[6] Maqsood, A., Kamran, K., and Gul, I. H., 2004, "Prediction of Thermal Conductivity of Granite Rocks From Porosity and Density Data at Normal Temperature and Pressure: In Situ Thermal Conductivity Measurements," J. Phys. D: Appl. Phys., **37**, pp. 3396–3401.

[7] Progelhof, R. C., Throne, J. L., and Ruetsch, R. R., 1976, "Methods for Predicting the Thermal Conductivity of Composite Systems: A Review," Polym. Eng. Sci., **16**(9), pp. 615–625.

[8] Springer, G., and Tsai, S., 1967, "Thermal Conductivities of Unidirectional Materials," J. Compos. Mater., **1**, pp. 166–173.

[9] Monji, K., Nakashima, K., Sogabe, Y., Miki, K., Tajima, F., and Shiraki, K., 1989, "Changes in Insulation of Wetsuits During Repetitive Exposure to Pressure," Undersea Biomed. Res., **16**(4), pp. 313–319.

[10] Norton, M. P., and Chan, C. Y. L., 1982, "Insulation Properties of Composite Cell Foamed Materials Suitable for Wet Suits," Appl. Energy, **12**, pp. 159–176.

[11] West, P. B., 1993, "Empirical Evaluation of Diving Wet Suit Material Heat Transfer and Thermal Conductivity," Heat Transfer Eng., **14**(4), pp. 74–80.

[12] Gebhart, B., and Mollendorf, J., 1978, "Buoyancy-Induced Flows in a Liquid Under Conditions in Which Density Extrema May Arise," J. Fluid Mech., **89**, pp. 673–707.

[13] Brandrup, J., Immergut, E. H., and Grulke, E. A., 1999, *Polymer Handbook*, 4th ed., John Wiley & Sons, New York.

[14] Gibson, L. J., and Ashby, M. F., 1997, *Cellular Solids*, 2nd ed., Cambridge University Press, Cambridge, UK.

[15] Norton, M. P., 1981, "Theoretical Considerations Concerning the Prediction of Diver Wet Suit Insulation Behavior With and Without Pressure Compensation," Appl. Energy, **9**, pp. 85–105.

[16] Ohsawa, T., Miwa, M., Nobuyuki, G., and Nakayama, A., 1979, "A Study of Composite Foams for Diving Suits Subjected to High Hydrostatic Pressure," J. Appl. Polym. Sci., **23**, pp. 1233–1245.

[17] Bardy, E. R., and Mollendorf, J. C., 2008, "Variation of the Thermal Conductivity of Elastomeric Foam," ASME Summer Heat Transfer Conference, Jacksonville, FL.