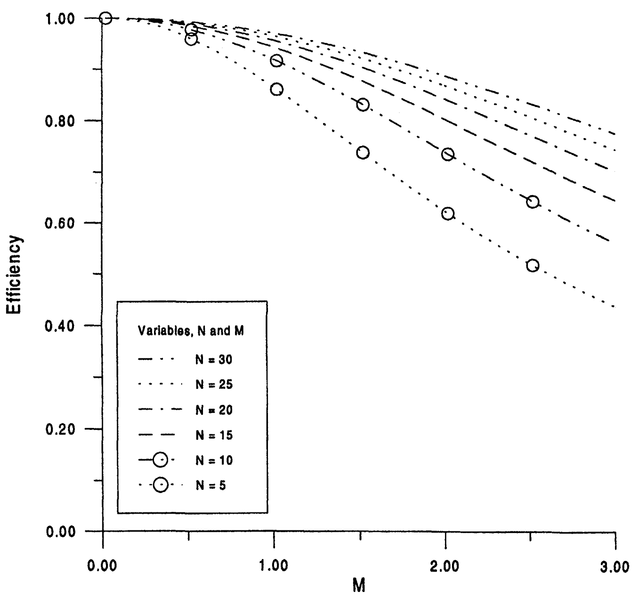

Fig. 6 Heat pipe fin efficiency as a function of M and N.

The other important parameter is n. In examining Eq. (5), n is very similar to m, defined in Eq. (4). The only difference between the two parameters is the convection coefficient and perimeter values. Looking at the ratio of the two terms

$$\frac{n}{m} = \left(\frac{h_i P_i}{h_0 P_0}\right)^{1/2} \tag{20}$$

Dunn and Reay[4] discuss the relative magnitudes of convection thermal resistance in heat pipes. They show that the resistance to convection on the outside of the heat pipe can range from 10 to 10^3°C/W, whereas the resistance through the heat pipe wick is on the order of 10°C/W. Thus, n will range in magnitude from m to $10m$. From Eq. (6), it can be seen that n will be large for heat pipe fins with large aspect ratios (L^2/A) or low thermal conductivity.

The variables a, n, and m were selected for convenience in comparing the standard fin with the heat pipe fin. A more convenient set of variables that apply only to the heat pipe fin are

$$M = am, \qquad N = an \tag{21}$$

Figure 6 shows how heat pipe fin efficiency varies with M and N. Figure 6 can be used as a design tool. For a particular heat pipe fin, the parameters N and M can be calculated. Then, using Fig. 6, the thermal efficiency of the fin can be found. As defined earlier in Eq. (14), the thermal efficiency is the fraction of the maximum heat transfer from the fin. The maximum heat transfer assumes the entire fin is at the fin base temperature. Unfortunately, N and M cannot be used to compare the heat pipe fin directly with a geometrically similar standard fin. The parameters a, n, and m are required for that comparison.

Conclusions

This paper has dealt with the comparison between a heat pipe fin and a standard fin. An analytical expression for the heat pipe fin temperature distribution and efficiency were obtained. The results show that heat pipe fins may not always be more efficient than standard fins; however, they usually are. The heat pipe fins are beneficial if weight is important, if the fins must be made from low thermal conductivity materials, or if high aspect ratio fins are needed.

References

[1]Peterson, G. P., *An Introduction to Heat Pipes: Modeling, Testing, and Applications*, Wiley, New York, 1994.

[2]Zhao, Z., and Avedisian, C. T., "Enhancing Forced Air Convection Heat Transfer from an Array of Parallel Plate Fins Using a Heat Pipe," *Proceedings of the 31st National Heat Transfer Conference*, Vol. 7, American Society of Mechanical Engineers, New York, 1996, pp. 53–60.

[3]Wei, J., Hijikata, K., and Inoue, T., "Fin Efficiency Enhancement Using a Gravity Assisted Planar Heat Pipe," *International Journal of Heat and Mass Transfer*, Vol. 40, No. 5, 1997, pp. 1045–1051.

[4]Dunn, P., and Reay, D. A., *Heat Pipes*, 2nd ed., Pergamon, Oxford, England, UK, 1978.

Comparison of Effective Thermal Conductivity and Contact Conductance of Fibrous Composites

S. R. Mirmira* and L. S. Fletcher†

Texas A&M University, College Station, Texas 77843

Introduction

FIBER-REINFORCED plastics are increasingly used in structural and thermal applications, necessitating an understanding of the thermophysical and mechanical properties. The strength and fatigue properties of these materials are reasonably well characterized and documented; however, limited information is available on the thermal properties, such as effective thermal conductivity. A review of published literature[1] indicates that the type of fiber and matrix, fiber volume fraction, and fiber orientation play critical roles in the effective thermal conductivity of the composite.

The objective of this experimental investigation is to present a comparison of the effective thermal conductivity and contact conductance for several different cured fibrous nonmetallic composites. Furthermore, this Note also discusses several previously conducted experimental studies and makes a comparison of these data with the results obtained in the present study.

The most prominent factors that affect the thermal conductivity of the composite materials are the thermal conductivity of the matrix and the fiber, and the fiber volume fraction.[2] There are a variety of polymers that are used as matrix materials for fiber-reinforced composites, including unsaturated polyesters, epoxies, polyethylene, and polycarbonates. Another critical factor to be considered for carbon fiber materials is the structure and type of carbon fiber; those based on a pitch precursor and those based on a polyacrylonitrile (PAN) precursor. These different precursors exhibit different thermal conductivity values. Further, graphite fibers, unlike carbon and glass fibers, exhibit a microstructural feature or texture that causes the transverse and longitudinal thermal conductivity to be anisotropic.

Other factors to be considered are the spatial characteristics and the interfacial thermal resistance between the fiber and the surrounding material. The spatial characteristics include the size, shape, and spacing of the fibers. Invariably, each fiber is in contact with the matrix, another fiber, a pore, or some combination thereof. Each of these boundaries will exhibit a resis-

Received Aug. 3, 1998; revision received Nov. 9, 1998; accepted for publication Nov. 19, 1998.

*Graduate Research Assistant, Conduction Heat Transfer Laboratory, Mechanical Engineering Department. Student Member AIAA.

†Thomas A. Dietz Professor, Conduction Heat Transfer Laboratory, Mechanical Engineering Department. Fellow AIAA.

tance to the heat flow through the material. The use of an effective wetting or sizing agent between the fiber and the surrounding matrix material lowers the interfacial resistance. The effect of porosity of the matrix material is similar to the effect of the spatial characteristics of the fibers. Pores act as barriers to heat flow, and therefore, lower the effective thermal conductivity of the material. It is thus obvious that the prediction of thermal conductivity by analytical models is rather complicated.

Experimental Program

Experimental Procedure

Experimental investigations were conducted to provide additional information on the effective thermal conductivity and contact conductance of selected fiber-reinforced composite materials. The materials selected, the experimental facility, and the experimental procedure adopted are described in this section.

Several commercially available fiber-reinforced organic materials commonly used in composite technology were selected for this study. Tables 1 and 2 list the resin and fiber type, weave type, and the fiber orientation of the composites. The matrices utilized were amine-cured epoxy (resin 1), epoxy (resin 2), and cyanate ester (resin 3), whereas the type of wetting/sizing agent used depended on the fiber type. The glass fibers were coated with amino–silane, the carbon fibers used in the fabrics were wetted with compatible epoxy finishes, whereas no wetting agent was employed on the carbon fibers used in the unicarbon laminates and the graphite fibers embedded in the cyanate ester matrix. Furthermore, the uncertainty in the fiber volume fraction for the samples tested was within ±2%. These composite materials were machined in the form of 2.54-cm (1.00-in.) diam laminate test specimens, 0.64 cm (0.25 in.) in thickness.

The test facility used in this experimental investigation included a vertical column consisting of a frame with sliding plates for the support of two combination heat source/sink specimen holder assemblies, the test samples, a load cell, and pneumatic bellows, as described by Mirmira et al.[3] A band heater was fitted around the upper flux-meter holder to provide the heat flux. Coolant (ethylene glycol) was circulated by means of flexible neoprene hoses connected to the lower flux-meter holder. The experimental facility was housed in a vacuum environment at a pressure of 1×10^{-5} torr that was maintained by an oil diffusion pump.

The vertical test column consisted of two electrolytic iron (certified by the National Institute of Standards and Technology) upper and lower flux meters and a central test specimen. The diameter of the flux meters and test samples was 2.54 cm (1.00 in.), and the length was 10.16 cm (4.0 in.) and 3.81 cm (1.5 in.), respectively. The composite sample was placed at the interface between the two electrolytic iron flux meters.

To ensure repeatability of the results, for each type of composite three different samples were tested. Thermal grease was applied between the specimen surfaces and the upper and lower flux meters for the thermal conductivity measurements. The electrolytic iron heat flux meters were instrumented with five 30-gauge, Teflon®/Teflon sheath, special limit of error type K chrome/alumel thermocouples, to enable the calculation of the temperature gradient, the temperature difference across the junction, and the heat flux normal to the interface. These thermocouples were located at 0.00635 m (0.250 in.) intervals.

Uncertainty Analysis

The Kline and McClintock[4] method was employed to determine the overall relative uncertainty in the effective thermal conductivity and thermal contact conductance of the composites. The overall uncertainty in the reported values of effective thermal conductivity and contact conductance of the composite materials are composed of various parameters. These parameters include, uncertainty in thermal conductivity of the base material (electrolytic iron), the heat flux, the temperature gradients within the iron flux meters, location tolerances for the thermocouples, the temperature readings, and the temperature difference across the interface. The average overall uncertainty

Table 1 Characteristics of cured fiber-reinforced composites[a]

Sample number, resin	Fiber	Weave	Orientation	Fiber volume, %
Resin 1 (Amine-cured epoxy)	None	None	Neat resin	0
Resin 2 (Epoxy)	None	None	Neat resin	0
1, resin 1	IM7	Plain weave	[0]	51.3
2, resin 1	E-glass	Style 7781	[(0/90)]	50.5
3, resin 1	AS4	Plain weave	[0]	58.0
4, resin 1	Carbon	Uniweave	[0]	50.7
5, resin 1	AS4	5 harness satin	[0]	51.1
6, resin 1	E-glass	Style 7781	[(0/90)]	49.7
7, resin 1	AS4	5 harness satin	[(0/90)]	48.5
8, resin 2	E-glass	Style 7781	[(0/90)]	50.5
9, resin 2	S-glass	Uniweave	[0]	47.3
10, resin 2	IM7	Uniweave	[0]	52.1
11, resin 2	AS4	Uniweave	[0]	57.1
12, resin 2	IM7	Uniweave	[0]	62.1
13, resin 2	AS4	Plain weave	[(0/90)]	52.3
14, resin 2	E-glass	Uniweave	[(0/90)]	47.0

[a]Carbon and glass fibers.

Table 2 Characteristics of cured fiber-reinforced composites[a]

Sample number, resin	Fiber	Manufacturer of fiber	Thermal conductivity (parallel to axis), W/mK	Fiber volume, %
Resin 3 (cyanate ester)	None	——	——	0
15, resin 3	DKAX	Amoco	900	55
16, resin 3	DKAX	——	——	65
17, resin 3	DKEX	——	617	55
18, resin 3	DKEX	——	——	65
19, resin 3	K22XX	Mitsubishi	600	55
20, resin 3	K22XX	——	——	65

[a]Pitch graphite fibers.

of the effective thermal conductivity of each sample was approximately ±4.1%.

The average overall uncertainty in the thermal contact conductance for each sample was the accumulation of the uncertainties mentioned for the effective thermal conductivity case, with the addition of uncertainties caused by the temperature difference across the junction and the dimensional tolerance for the cross-sectional area of the sample, and this uncertainty has been determined as ±5.0%.

Results and Discussion

Figure 1 indicates the effective transverse thermal conductivity of the three pure resin matrices, the 14 composite samples consisting of either glass or carbon fibers embedded in an epoxy, and six samples consisting of graphite fibers in a cyanate ester matrix, all as a function of temperature. These composites were manufactured by utilizing AS4 and IM7 PAN-based carbon fibers, pitch-based graphite fibers (DKA X, DKE X, and K22XX), and S-Glass and E-Glass fibers. The diameters of the fibers were ~10 μ and the fiber volume fraction varied from 47 to 65%. As indicated, the effective thermal conductivity of the pure resin materials was the lowest (~0.22 and 0.3 W/mK) and was rather independent of temperature. With the addition of fibers to the pure resin, the transverse thermal conductivity increased and this value for a majority of the carbon and glass fiber composites was in the range of 0.4–0.8 W/mK, and were rather independent of temperature. The exception being sample 7 (resin 1, AS4 fibers, V_f = 48.5%), which had a relatively higher effective thermal conductivity value, as well as a slight increase in thermal conductivity with increasing temperature.

The transverse effective thermal conductivity of graphite fiber composites is also shown in Fig. 1. Because of the inherent high thermal conductivity of the pitch graphite fibers, the effective thermal conductivity of these composites are approximately one order of magnitude higher than composites consisting of carbon and glass fibers. Between the two fiber volume fractions indicated (55 and 65%), the 65% fiber volume fraction sample possessed a slightly higher thermal conductivity. This is to be expected considering that the thermal conductivity of the fiber is significantly higher than the matrix material.

In general, it appears that the composites consisting of carbon fibers [AS4 and IM7 (open symbols in Fig. 1)] possess a greater effective thermal conductivity than the polymers containing glass fibers [E and S glass (closed symbols in Fig. 1)]. Further, a comparison of composites that are similar in all aspects (samples 2 and 4 and 11 and 14), except for the type of fiber, indicates that the composites consisting of AS4 carbon fibers possess a higher effective thermal conductivity than

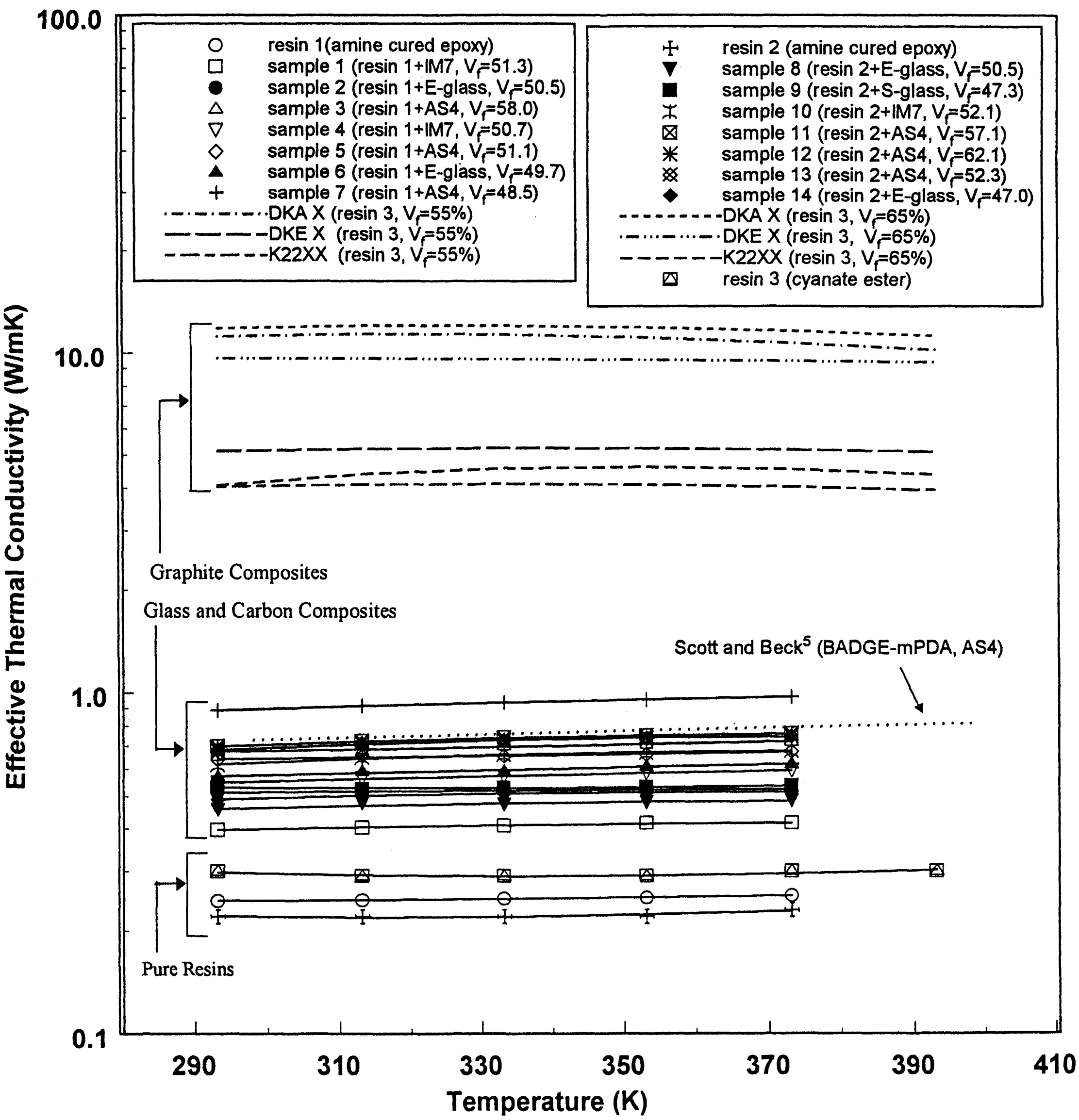

Fig. 1 Effective thermal conductivity of composite materials as a function of mean interface temperature.[3,6]

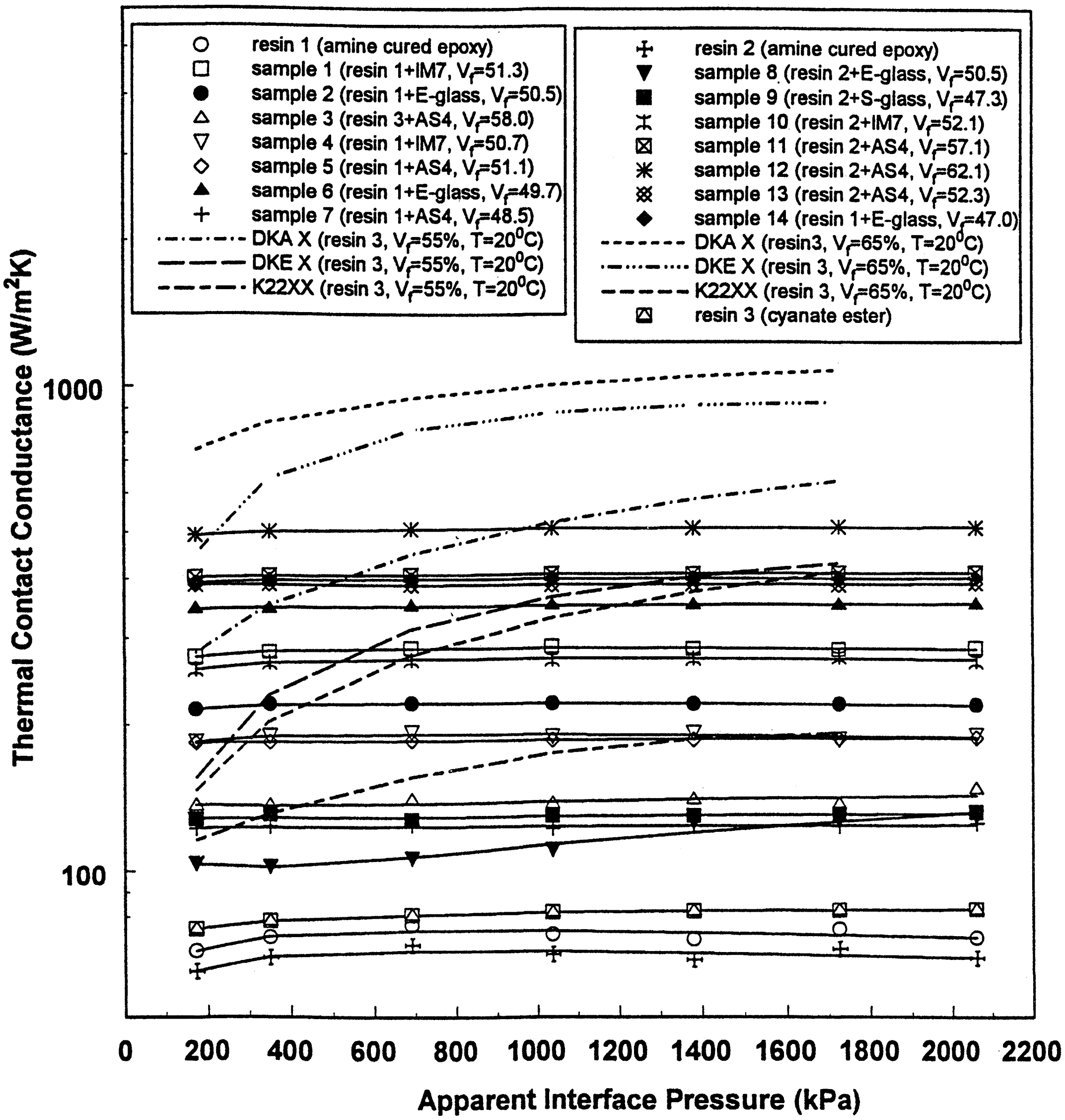

Fig. 2 Thermal contact conductance of composite materials as a function of apparent interface pressure.

those with IM7 carbon fibers. This may be attributed to the fact that the AS4 fibers possess a higher transverse thermal conductivity (1.8 W/mK) than IM7 fibers (1.19 W/mK). A comparison of two samples (6 and 8) that have the same weave, orientation, fiber type, approximately equal fiber volume fraction, but different resin material, indicates that resin 1 (amine-cured epoxy) is capable of dissipating a greater amount of energy than resin 2 (amine-cured epoxy). This conforms to the results obtained for pure resin samples.

Figure 1 also shows experimental data along with those obtained by Scott and Beck[5] for fibrous composite materials consisting of surface-treated AS4 fibers in a BADGE-mPDA epoxy matrix over a temperature range of 298–398 K (also see Ref. 6). Their results are ~0.8 W/mK and are comparable to the results obtained for the composite consisting of 57.1% volume fraction AS4 carbon fibers embedded in resin 2 (sample 11).

Figure 2 shows the thermal contact conductance for the epoxy fiber-reinforced composites as a function of apparent interface pressure. The values range from approximately 75–1050 W/m^{2}K. The thermal contact conductance of a material is strongly influenced by a combination of the thermal conductivity of the matrix and fiber and the thickness. On one hand, the thermal contact conductance values for the composites of resins 1 and 2 are invariant with pressure. This is because the thickness of the samples does not change with pressure. On the other hand, the thermal contact conductance of pitch graphite fibers embedded in a cyanate ester increased with an increase in pressure. A possible explanation for this is that with the application of pressure, the interfacial thermal resistance between the fiber and matrix is reduced, thus facilitating easier transport of energy through the material. This effect may be more pronounced in the case of graphite fibers in the cyanate ester matrix because of the lack of a wetting agent. Furthermore, the cyanate ester material tended to deform with the application of pressure and was more susceptible to a reduction in sample thickness. It is apparent that the neat resins, which have the lowest thermal conductivity (Fig. 1), possess the lowest thermal contact conductance values.

Conclusions and Recommendations

This Note presents a comparison of the effective thermal conductivity and contact conductance of a wide range of carbon, pitch graphite, and glass fiber-reinforced plastic materials of different weave types. These data would prove to be very useful to engineers involved in the design of aerospace and electronic systems' heat sinks. It appears that the pitch graphite fiber composites possess the highest effective thermal conductivity and contact conductance. Furthermore, it is evident that the thermal properties of these materials are dependent on various parameters, the influence of which should be investigated. Presently, there does not exist a comprehensive model that accounts for all of the parameters that influence the thermal conductivity of these materials. The major obstacles are determining the interfacial resistance between the various components of the composite, developing an accurate method to model the transverse anisotropic nature of the carbon fibers, and accounting for the randomly distributed and oriented pores.

References

[1]Ayers, G. H., and Fletcher, L. S., "A Review of Thermal Conductivity of Graphite Reinforced Metal Matrix Composite Materials," *Journal of Thermophysics and Heat Transfer*, Vol. 12, No. 1, 1998, pp. 10–16.

[2]Rolfes, R., and Hammerschmidt, U., "Transverse Thermal Conductivity of CFRP Laminates," *Composites, Science, and Technology*, Vol. 54, Feb. 1995, pp. 45–54.

[3]Mirmira, S. R., Jackson, M. C., and Fletcher, L. S. "Thermal Conductivity and Contact Conductance of Graphite Fiber Composites," AIAA Paper 98-2760, June 1998.

[4]Kline, S. J., and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, Vol. 75, No. 1, 1953, pp. 1–8.

[5]Scott, E. P., and Beck, J. V., "Estimation of Thermal Properties in Epoxy Matrix/Carbon Fiber Composite Materials," *Journal of Composite Materials*, Vol. 26, No. 1, 1992, pp. 132–149.

[6]Mirmira, S. R., Renzi, D. F., and Fletcher, L. S., "Thermal Conductivity and Thermal Contact Conductance of Fiber Reinforced Composite Materials," *Proceedings of the 11th International Heat Transfer Conference*, Vol. 7, Taylor and Francis, Washington, DC, 1998, pp. 83–87.

United States Postal Service

Statement of Ownership, Management, and Circulation

1. Publication Title	2. Publication Number	3. Filing Date
Journal of Thermophysics and Heat Transfer	0 8 7 7 - 8 7 2 2	3/15/99
4. Issue Frequency: Quarterly	5. Number of Issues Published Annually: 4	6. Annual Subscription Price: $165/$335

7. Complete Mailing Address of Known Office of Publication *(Not printer) (Street, city, county, state, and ZIP+4)*
AIAA, 1801 Alexander Bell Drive,Reston,VA, 20191
Contact Person: Deanna Miller
Telephone: 703.264.7500

8. Complete Mailing Address of Headquarters or General Business Office of Publisher *(Not printer)*
AIAA (above)

9. Full Names and Complete Mailing Addresses of Publisher, Editor, and Managing Editor *(Do not leave blank)*

Publisher *(Name and complete mailing address)*
Norma Brennan (AIAA above)

Editor *(Name and complete mailing address)*
Alfred L. Crosbie,Dept. of Mechanical Engineering,University of Missouri-Rolla, Rolla, MO

Managing Editor *(Name and complete mailing address)*
Deanna Miller (AIAA above)

10. Owner *(Do not leave blank. If the publication is owned by a corporation, give the name and address of the corporation immediately followed by the names and addresses of all stockholders owning or holding 1 percent or more of the total amount of stock. If not owned by a corporation, give the names and addresses of the individual owners. If owned by a partnership or other unincorporated firm, give its name and address as well as those of each individual owner. If the publication is published by a nonprofit organization, give its name and address.)*

Full Name	Complete Mailing Address
American Institute of Aeronautics and Astronautics (AIAA)	1801 Alexander Bell Dr., Reston,VA,20191

11. Known Bondholders, Mortgagees, and Other Security Holders Owning or Holding 1 Percent or More of Total Amount of Bonds, Mortgages, or Other Securities. If none, check box ☐ None

Full Name	Complete Mailing Address

12. Tax Status *(For completion by nonprofit organizations authorized to mail at nonprofit rates) (Check one)*
The purpose, function, and nonprofit status of this organization and the exempt status for federal income tax purposes:
☒ Has Not Changed During Preceding 12 Months
☐ Has Changed During Preceding 12 Months *(Publisher must submit explanation of change with this statement)*

PS Form 3526, September 1998 *(See Instructions on Reverse)*

13. Publication Title: Journal of Thermophysics and Heat Transfer
14. Issue Date for Circulation Data Below: Apr-Jun 1999

15. Extent and Nature of Circulation	Average No. Copies Each Issue During Preceding 12 Months	No. Copies of Single Issue Published Nearest to Filing Date
a. Total Number of Copies *(Net press run)*	1575	1900
b. Paid and/or Requested Circulation (1) Paid/Requested Outside-County Mail Subscriptions Stated on Form 3541. *(Include advertiser's proof and exchange copies)*	1017	1394
(2) Paid In-County Subscriptions *(Include advertiser's proof and exchange copies)*		
(3) Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Non-USPS Paid Distribution		
(4) Other Classes Mailed Through the USPS		
c. Total Paid and/or Requested Circulation *[Sum of 15b. (1), (2),(3),and (4)]*	1017	1394
d. Free Distribution by Mail *(Samples, compliment ary, and other free)* (1) Outside-County as Stated on Form 3541	19	19
(2) In-County as Stated on Form 3541		
(3) Other Classes Mailed Through the USPS		
e. Free Distribution Outside the Mail *(Carriers or other means)*		
f. Total Free Distribution *(Sum of 15d. and 15e.)*	19	19
g. Total Distribution *(Sum of 15c. and 15f)*	1036	1413
h. Copies not Distributed	538	487
i. Total *(Sum of 15g. and h.)*	1575	1900
j. Percent Paid and/or Requested Circulation *(15c. divided by 15g. times 100)*	65%	73.4%

16. Publication of Statement of Ownership
☐ Publication required. Will be printed in the Apr-Jun 1999 issue of this publication. ☐ Publication not required.

17. Signature and Title of Editor, Publisher, Business Manager, or Owner: Norma Brennan, Publications Director — Date: 3/15/99

I certify that all information furnished on this form is true and complete. I understand that anyone who furnishes false or misleading information on this form or who omits material or information requested on the form may be subject to criminal sanctions (including fines and imprisonment) and/or civil sanctions (including civil penalties).

Instructions to Publishers

1. Complete and file one copy of this form with your postmaster annually on or before October 1. Keep a copy of the completed form for your records.
2. In cases where the stockholder or security holder is a trustee, include in items 10 and 11 the name of the person or corporation for whom the trustee is acting. Also include the names and addresses of individuals who are stockholders who own or hold 1 percent or more of the total amount of bonds, mortgages, or other securities of the publishing corporation. In item 11, if none, check the box. Use blank sheets if more space is required.
3. Be sure to furnish all circulation information called for in item 15. Free circulation must be shown in items 15d, e, and f.
4. Item 15h., Copies not Distributed, must include (1) newsstand copies originally stated on Form 3541, and returned to the publisher, (2) estimated returns from news agents, and (3), copies for office use, leftovers, spoiled, and all other copies not distributed.
5. If the publication had Periodicals authorization as a general or requester publication, this Statement of Ownership, Management, and Circulation must be published; it must be printed in any issue in October or, if the publication is not published during October, the first issue printed after October.
6. In item 16, indicate the date of the issue in which this Statement of Ownership will be published.
7. Item 17 must be signed.

Failure to file or publish a statement of ownership may lead to suspension of Periodocals authorization.

PS Form 3526, September 1998 *(Reverse)*