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Anisotropic Thermal Response of Packed Copper Wire

The apparent thermal conductivity of packed copper wire test specimens was measured parallel and perpendicular to the axis of the wire using laser flash, transient plane source, and transmittance test methods. Approximately 50% wire packing efficiency was produced in the specimens using either 670- or 925-μm-diameter copper wires that both had an insulation coating thickness of 37 μm. The interstices were filled with a conventional varnish material and also contained some remnant porosity. The apparent thermal conductivity perpendicular to the wire axis was about 0.5–1 W/mK, whereas it was over 200 W/mK in the parallel direction. The Kanzaki model and an finite element analysis (FEA) model were found to reasonably predict the apparent thermal conductivity perpendicular to the wires but thermal conductivity percolation from nonideal wire-packing may result in their underestimation of it. [DOI: 10.1115/1.4035972]

Keywords: apparent thermal conductivity, transverse isotropy, laser flash, transient plane source, thermal transmittance, representative volume element, thermal conductivity percolation

1 Introduction

The successful management of Joule-heating-losses in copper-wound electric motors enables the achievement of maximized operational efficiency and lifetime. Motor cooling may be actively pursued via air- or liquid-cooling of the exposed wires, such as those shown in Fig. 1, or via passive-cooling via heat flow into the adjacent stator laminates as illustrated in Fig. 2, or through both.

The importance of the thermal transfer along (or axially or parallel) or across (or transversely or perpendicular) the copper-windings matters if the sought-after cooling of the copper windings is external or internal to the motor, respectively.

External cooling directly applied to the motor end windings takes advantage of copper's high thermal conductivity (κ) and the removal of heat that the copper wires inherently cause.

However, the efficacy of internal cooling (i.e., heat transfer from the copper wires into the adjacent stator) is limited by the heat transfer perpendicular to the wound-wire and affected by the interstitial constituents that can include insulative wire-coatings, organic fillers, and porosity; constituents that all typically have low bulk κ's themselves. Additionally, a thermal resistance can be expected at the interface of each constituent which will further impede the overall thermal management.

Here, the introduction of the term "apparent thermal conductivity" or (κ_app) is warranted. The sum of all the constituent κ's and system parasitics (e.g., interfacial thermal resistance losses among them) results in and justifies the use of κ_app. The κ of each constituent is an intrinsic material property whereas κ_app is not; κ_app is a material system characteristic. *This study's measured and interpreted thermal responses of packed copper wire are hereafter referred to as* κ*_app.*

A prerequisite to the understanding (and any subsequent maximization of the heat transfer perpendicular to the aligned copper wires) is the confident experimental measurement of such thermal responses with controlled specimens. Based on that, there were several motivating factors for the present study:

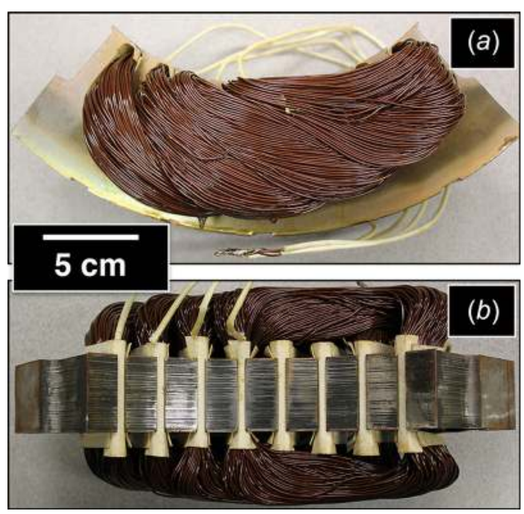

Fig. 1 Top (*a*) and side (*b*) views of a radially sectioned, copper-wire-wound laminated steel electric motor

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Contributed by the Heat Transfer Division of ASME for publication in the Journal of Thermal Science and Engineering Applications. Manuscript received September 6, 2016; final manuscript received February 5, 2017; published online April 19, 2017. Assoc. Editor: Hongbin Ma.

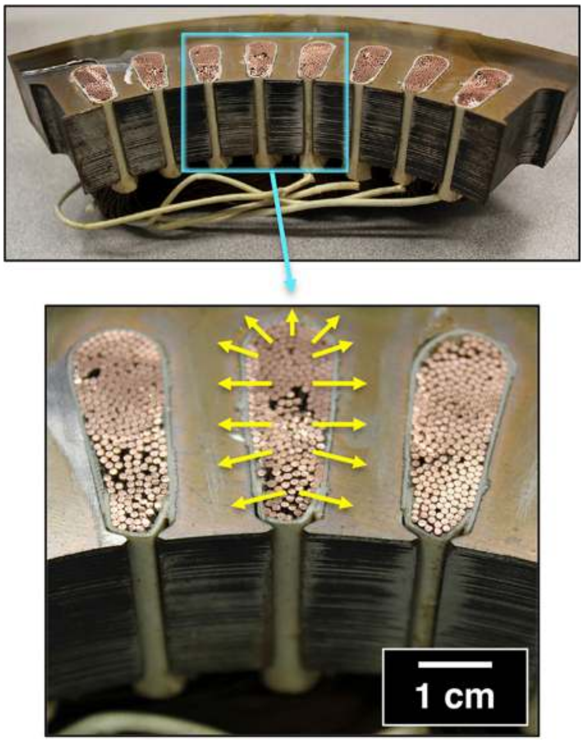

Fig. 2 Sectioned view showing the copper-wire packing within slot liners. Arrows in the bottom image represent the direction of potential heat transfer from the copper wires.

- Measure and interpret directional-dependence of κ_app of packed and aligned copper wire (a transversely isotropic structure).
- Utilize and contrast three different established κ test methods for their measurements, and assess and contrast the efficacy of each method in the context of the packed copper-wire structure and scale.
- Develop a method to fabricate representative test specimens that contain relevant interstitial constituents, and whose specimen size facilitates κ_app measurement.
- Examine if wire-diameter size can affect κ_app response.

As will be shown, the κ_app parallel to the wire axis was over two orders of magnitude higher than κ_app perpendicular to the wires, each of the test methods had their own advantages and disadvantages, a process was developed to make suitable test coupons for κ_app measurements, and the examined wire diameters produced no observable difference in κ_app.

2 Experimental Procedure

2.1 Specimen Fabrication. Varnish-impregnated copper wire samples were fabricated through a multiple-step process. Relatively large cubes were fabricated to permit sample harvesting for thermal property measurement.

Two commercially available (MWS Wire Industries, Westlake Village, CA) 19- and 22-gauge wires were used (925- and 670-μm-diameter, respectively).[2] Both conform to National Electrical Manufacturers Association (NEMA) standard MW35C with a 200 °C temperature rating and a 37-μm-thick polyester-amide-imide insulation coating. Polished cross sections of both wire diameters are shown in Fig. 3.

[2]Certain commercial materials or equipment are identified in this paper to adequately specify the experimental procedure. This in no way implies their endorsement by the Oak Ridge National Laboratory, UT-Battelle, the U.S. Department of Energy, nor the coauthors' employers or institutions nor that these materials and equipment are necessarily the best choices for these purposes.

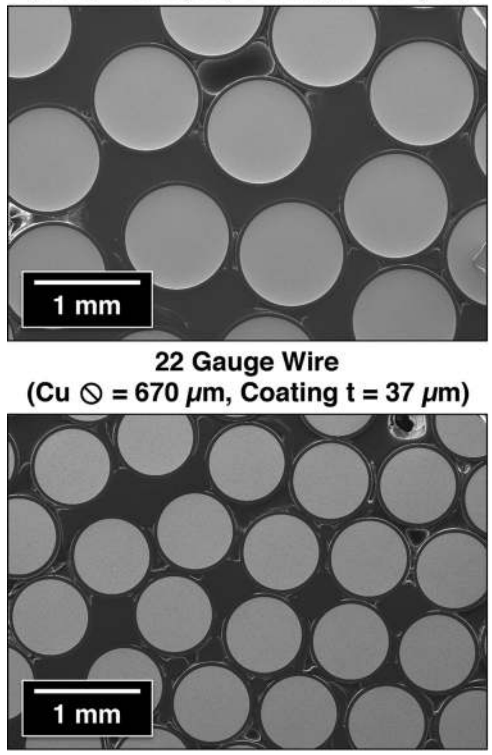

Fig. 3 Polished cross sections of the two wire sizes used to fabricate test specimens. ⃠ is the diameter and *t* is the thickness.

Fifty single wires were combined and wrapped around a 70 mm × 19 mm mandrel to form a bundle. Two wire bundles were combined at a time and cut to a length of 60–65 mm. This aided in the ability to keep count of the number of wires in each cube to accurately calculate the fill factor for each wire gauge. Fill factor refers to the fraction of copper within the wire bundles, excluding wire insulation coating. Wire bundles were vertically inserted into a Teflon fixture and packed tightly and consistently as possible. Ideal or perfect packing was not expected due to the use of manual packing of a human operator. The 19-gauge wire cubes had 2150 wires each for an idealized wire fill factor of 54%, and the 22-gauge wire cubes had 3800 wires each for an idealized fill factor of 58%. As will be discussed, estimated fill factors using density and image analysis methods were not necessarily equal to those idealized values.

The wire-filled fixture was placed into a vacuum chamber, and varnish (Dolphon® CC-1105, John C. Dolph Company, Monmouth Junction, NJ) was poured on top of the fixture submerging the wires. A vacuum pressure of 98 kPa (0.97 atmospheres or 29 in. Hg) was applied for 45 min with the intent to remove entrapped air in the cubes. The cubes were removed from the vacuum chamber and placed inside a preheated furnace at 135 °C and soaked for 4 h.

A schematic of the wire packing and ground exteriors of fabricated cubes are shown in Fig. 4. The fabricated cubes were then ground and sectioned to fabricate test specimens for thermal property testing. An example of that is shown in Fig. 5. Parameters relevant to the processed packed copper wire cubes are shown in Table 1.

Two methods were compared to determine wire fill factor or packing efficiency. The first is a rule-of-mixtures method for the composite structure based on the discrete densities of its constituents. Those constituent densities are provided in Table 1. The second method was a visual method that uses an image of the surface and determines the fraction of copper to other components. Both

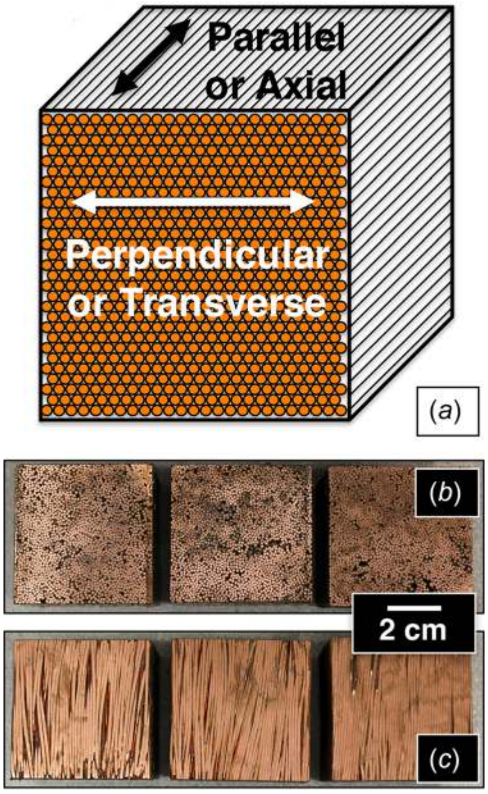

Fig. 4 Schematic (*a*) of wire orientations in the processed cubes, and examples of (*b*)-(*c*) the two orientations of ground sections thereof

methods implicitly assume the existence of homogeneity. The inconsistency in the fill factor estimations for the two methods (see Table 1) highlights the fact that seemingly trivial measurements can have complex uncertainties associated with them. But

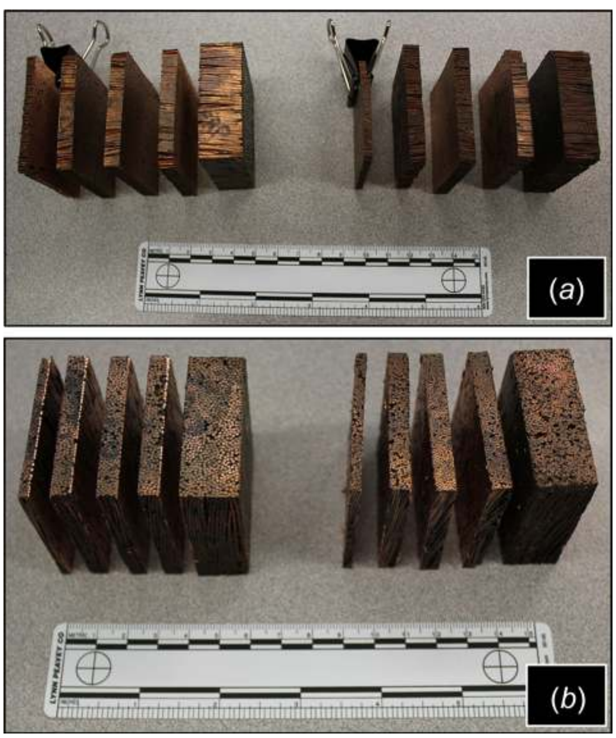

Fig. 5 Slab-sectionings of the processed cubes for thermal conductivity specimen testing

as will be seen and discussed, these disparities arguably do not compromise the interpretation of the observed thermal property trends because their introduced uncertainty does not alter the fact that the overall thermal conductivity perpendicular to the wires is quite low.

2.2 Thermal Testing. Three different thermal testing methods were used: flash diffusivity [1], transient plane source (TPS) [2], and thermal transmittance [3]. Some key characteristics of each method are listed in Table 2, and they are pictorially shown in Figs. 6(*a*)–6(*c*). Thermal conductivity is estimated from transient-based thermal excitation for the flash diffusivity and TPS methods, and from steady-state thermal excitation for the thermal transmittance method. The rationale to use different test methods was to judge the efficacy for use of each with these anisotropic packed copper wire specimens and equivalency of their results. Such an approach can be useful in determining if there are shortcomings of a method in the context of the chosen test material or to confirm that different methods produce equivalent results (which they ideally should) [4].

In addition to the methods being used to estimate the thermal conductivity of packed copper wire, their equivalency of results was judged by estimating the thermal conductivity of (monolithic, isotropic, and homogeneous) soda lime silicate glass (a low thermal conductivity), and a polycrystalline silicon carbide (a high thermal conductivity).

2.2.1 Flash Diffusivity. Thermal conductivity (κ) of bulk samples is often calculated using measurements of thermal diffusivity (α) with the flash diffusivity method [1], specific heat (Cp), and density (ρ) and using Eq. (1)

$$\kappa = \alpha \rho C_p \tag{1}$$

Specific heat and density were calculated for the herein described packed copper test coupons using the rule of mixtures, and Cp and ρ literature values of pure copper and varnish, and calculated volume fractions thereof. The effect of the wire insulation was dismissed in the consideration because of the relatively small volume it occupies.

The laser flash technique is very common from room temperature and above mainly because it translates a temperature and heat flux measurement into a time domain measurement of transient intensity versus time. Under one-dimensional heat flow conditions, thermal diffusivity is simply expressed in the Parker equation [5]

$$\alpha = 0.138 d^2 / t_{0.5} \tag{2}$$

where d is the sample thickness and $t_{0.5}$ is the half-rise time. Further heat loss corrections using the Cowan [6] or Clark and Taylor [7] methods may be needed.

Typical specimens are disks with a 12.7 mm diameter and few millimeters in thickness such as shown in Fig. 6(*a*). For testing, a 10-mm-diameter spot size is laser-flashed onto the specimen's 12.7-mm diameter-surface. Note the key for the flash diffusivity method is the one-dimensional heat flow condition so it requires the sample diameter-to-thickness ratio be large.

2.2.2 Transient Plane Source. The second employed thermal conductivity measurement was the transient plane source (TPS) or the hot disk method [2]. It uses a thin, flexible heater/sensor containing a double-spiral nickel wire sandwiched between thin Kapton films. Two bulk specimens are required, see Fig. 6(*b*), and the heater temperature during the constant-power heating is recorded using the temperature coefficient of resistance (TRC) of nickel.

The TPS method was used to measure the thermal conductivity between two large blocks of packed copper wire (see Fig. 6(*b*)) in both perpendicular and parallel directions. The size of such large

Table 1 Apparent bulk density and volume percentage of relevant materials and constituents

Material	Bulk or apparent density (g cm^{-3})	Calculated volume percentage copper (based on density)	Calculated volume percentage copper (from image analysis)
Cu-Wire and Varnish 19-Ga	5.2	52%	67%
Cu-Wire and Varnish 22-Ga	4.6	45%	65%
Wire coating	1.4	n/a	n/a
Varnish	1.0	n/a	n/a
Copper	9.0	n/a	n/a

Table 2 Comparison of thermal testing methods

	Laser flash	Transient plane source	Thermal transmittance
Standard	ASTM E1461	ISO 22007-2	ASTM D5470
Heating state	Transient	Transient	Steady-state
Specimen	Thin disk or plate	Thick specimen	Disk or plate
Measurement uncertainty	±5%	2–5%	<18%

blocks is desirable since the TPS method gets signal from the two semispherical volumes (with no boundaries in ideal conditions).

2.2.3 Thermal Transmittance. The setup used to measure apparent thermal conductivity through a steady-state thermal transmission is shown in Fig. 6(*c*). Unlike the flash diffusivity and TPS methods, the thermal transmittance method is used to estimate thermal conductivity based on the establishment of steady-state thermal transfer during its testing.

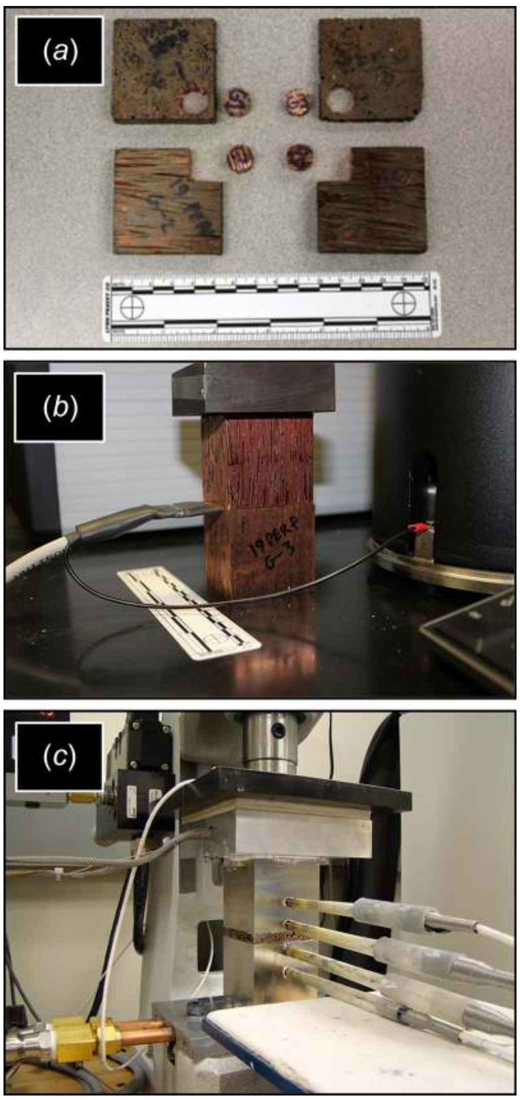

Fig. 6 Test specimen harvesting (*a*) for laser flash testing, and test setups for (*b*) transient plane source and (*c*) thermal transmission testing

The test apparatus was built in accordance with ASTM Standard D5470 [3,8]. It uses four resistance temperature detection probes to measure the temperature and heat flow through the top and bottom metering blocks. That information is used to determine the thermal resistance of the sample. The sample is square with 50.8-mm-long sides. The sample thickness varied from 3.2 to 6.4 mm for measurements perpendicular to the wires, and 6.4 to 19.2 mm for measurements parallel to the wires.

The setup has two advantages. First, it is a direct measurement. The only property that needs to be known about the sample to perform an accurate measurement is its thickness. Second, the heat flow is strictly one-dimensional, so it can measure the properties of the material in one direction independently of any other direction.

The disadvantage to the setup is the requirement of the use of a thermal interface material (such as thermal grease) between the sample and the metering blocks. Whether or not that interface effect can be predicted and subtracted from the result is dependent on the surface properties of the sample and the repeatability of the interface. When it is neither predictable nor repeatable, then its effect adds to uncertainty of the calculated measurement.

3 Results and Discussion

3.1 Monolithic Materials. The equivalency of measured thermal conductivity produced by the three test method depended on the magnitude of the material thermal conductivity. Their results are provided in Table 3. The three test methods produced nearly identical thermal conductivity results for the soda-lime silicate glass; however, while the laser flash and thermal transmittance methods produce equivalent results for the silicon carbide, the TPS result was about 20% lower.

The TPS method is more likely to have larger errors for high thermal conductivity materials which are sensitive to test parameters and sample sizes. Error arises from the requirement for infinitely larger samples and high heating power. For smaller samples, the boundary effect and local anisotropy could both contribute the uncertainties.

3.2 Packed Copper Wire

3.2.1 Overall Thermal Response. Viewing the collective results from all the three test methods, it is evident that the κ_app of the packed copper wire was over two orders of magnitude higher in the direction parallel to the wires than perpendicular to them. The measured results are provided in Table 3. The former

Table 3 Measured thermal conductivities as a function of test method

Material	Apparent thermal conductivity κ_app (W/mK)		
	Laser flash E1461	Transient plane source ISO 22007-2	Thermal transmittance ASTM D5470
Cu-wire and varnish, parallel or axial, 19-Ga	238	[a]	
Cu-wire and varnish, perpendicular or transverse, 19-Ga	0.55	[a]	1.0–1.2
Cu-wire and varnish, parallel or axial, 22-Ga	212	[a]	
Cu-wire and varnish, perpendicular or transverse, 22-Ga	0.52	[a]	1.0–1.2
Varnish[b]		0.19	
Silicate glass[b] (soda-lime) monolithic	1.0	1.02	1.08
SiC[b] (polycrystalline) hot-pressed monolithic	166	124	157

[a]Technique unfavorable for highly anisotropic materials.
[b]Actual κ measured (not κ_app).

was over 200 W/mK while the latter was only 0.5 to 1 W/mK for a wire packing efficiency (or volume fraction of copper) of approximately 50%. Such a large difference in κ_app has been recognized to previously exist [9]. As a reference, the k of pure bulk copper is 375–400 W/mK at room temperature.

The flash diffusivity produced measured apparent thermal conductivities in the perpendicular direction that were about one-half those measured with the thermal transmittance method ($\sim$ 0.5 W/mK versus $\sim$ 1 W/mK). This is likely a consequence of the uncertainties associated with each test method and those of the specimens used for each. The flash diffusivity method uses a relatively thin specimen for one-dimensional heat flow. The number of wires is low relative to this dimension, and that effect introduces some uncertainty (discussed in Sec. 3.2.2). For the thermal transmittance method, the exposed edge areas may be relatively large and any heat loss is unaccounted for. Despite these uncertainties, the measured thermal conductivity difference between these two methods was only approximately 0.5 W/mK.

The measured κ_app responses of the packed copper wires consisting of either 670- or 925-μm-diameter wires did not exhibit significant differences in the direction perpendicular to the wires at a packing efficiency of $\sim$ 50%. However, the 925-μm-diameter wire samples had about a 10% higher κ_app than the 670-μm-diameter wire samples in the parallel direction; this is consistent with the former having a slightly higher packing efficiency than the latter.

The observed anisotropy was the consequence of several phenomena. Idealized close packaging did not exist in these packed copper wire samples, so the (perpendicular) thermal transfer between next-nearest neighbor of copper wires was hindered by the low thermal conductivity of the interstitial varnish and the insulative wire coating, as well as thermal resistance loss between every constituent interface (and there are many such interfaces in this system). The varnish has a very low thermal conductivity (less than 0.2 W/mK measured with the TPS method and monolithic varnish samples). The polymeric insulative wire coating also has a low thermal conductivity (less than 1 W/mK), and any residual entrapped porosity will also hinder that perpendicular thermal transfer.

3.2.2 Statistical Homogeneity and Specimen Size. Thermal conductivity is an intrinsic material property that is independent of specimen size and shape, and whose measured value should also be independent of the employed test method. The measurement of κ of the monolithic (and statistically homogeneous) silicate glass and polycrystalline SiC using the herein described test methods illustrate this.

But if the size of the test specimen (or size of a component) is too small with respect to its material's microstructure or architecture, then the scale of the discrete constituents of the architecture can noticeably perturb the measured global response. In this case, statistical homogeneity is not preserved, and an intrinsic material property, like thermal conductivity, becomes an extrinsic material property because its overall measured response is dependent on the specimen size or shape. For the present study, this size-scaling issue pertains to the κ_app measured perpendicular to the aligned copper wires and not parallel to them.

The smallest volume for which statistical homogeneity is achieved is referred to as the representative volume element (RVE). Each of the constituents within a material has its own one-dimensional characteristic length (L), and the RVE is some multiple of L (of the largest constituent in the system) depending on whether a transport (e.g., thermal conductivity, electrical conductivity, elasticity) or structural or breakdown thresholds (e.g., tensile strength) is being considered. Statistical homogeneity is considered to be achieved for transport properties when the RVE is $\sim$ 10–15 L [10] and RVE $\sim$ 30–50 L for structural properties [11,12].

In the context of packed copper wire and the measured κ_app response perpendicular to their aligned axes, the largest constituent in its system is (or should be) the copper wire itself. If the wire diameter is reasonably taken to be the largest L in the system (670 μm or 925 μm for the two utilized wires in these trials), then the statistical homogeneity is anticipated if the specimen (or component) size or dimension perpendicular to the wires is at least $\sim$6 mm or $\sim$9 mm, respectively.

These relatively large estimated sizes, in regard to the component size and specimen sizes for the herein employed thermal conductivity test methods employed here, suggest that statistical homogeneity may never be achieved in either and that a relatively large amount of scatter in κ_app can be chronically expected for them all.

As an example for the component, statistical homogeneity may not even circumferentially exist throughout the slot's radial dimension with the shown wires (see Fig. 2). If the minimization of scatter in κ_app was important, then that could be potentially remedied if smaller wires were instead utilized whose diameters were less than $\sim$10% than the narrowest dimension of the slot winding.

Statistical homogeneity will also be addressed in the proceeding Secs. 3.2.3–3.2.5 for each of the specimens used with three thermal conductivity test methods. As will be seen, the achievement of statistical homogeneity likely did not occur.

3.2.3 Flash Diffusivity Response. The low κ_app values in the perpendicular direction indicate the copper wires were isolated and did not affect heat conduction in this direction. On the other hand, heat conduction parallel to the copper wires shows the wire has a significant impact. The measured values from 212 to 238 W/mK are 53–59% of pure copper at room temperature, and the $\sim$10% higher κ_app for the 19-Ga wire system is consistent with it having a higher packing efficiency compared to the 22-Ga wire system.

The specimen thickness was only a few millimeters, so statistical homogeneity for the perpendicular direction for this test method was likely not achieved, despite the confidence in actual measured response and subsequent estimation of κ_app. More tests to produce more confident and interpretative statistics of scatter are needed.

3.2.4 Transient Plane Source Response. The TPS method did not produce trustworthy κ_app results for the packed copper wire samples. The anisotropic analysis mode of the TPS method was tried varying test analysis time and heat power. Such a variation of testing was pursued because the measured response (κ_app) with this method is a consequence of the convolution of parallel (κ_para) and perpendicular (κ_perp) thermal transfer in the sample, the recognized anisotropy of these tests samples, and the sought-after objective to achieve consistent results independent of the test conditions.

The following three conditions were tested by calculating κ_app at different time intervals:[3]

(1) Two watts heating for 20 s: κ_para = 266 W/mK; κ_perp = 0.023 W/mK. The κ_para value was reasonable but the κ_perp value was too low.
(2) One watts for 10 s: κ_para = 211 W/mK; κ_perp = 0.330 W/mK. The κ_para value was lower but the κ_perp value was close to that of varnish.
(3) One watts for 20 s: κ_para = 198 W/mK; κ_perp = 0.214 W/mK. The κ_para dropped below 200 W/mK and the κ_perp value also decreased.

These results show that the TPS anisotropic analysis can produce plausible κ_app values in the perpendicular direction of these samples in the 10 s testing time where the thermal transfer of the interstices dominates. However, at longer times (about 20 s), where heat conduction of the copper dominates, that test duration perhaps best represents the κ_app of both the parallel and perpendicular directions. Given those observations, it is reasonable to conclude condition #2 was better for these test samples. However, these tests also indicated that the TPS method is highly dependent on the parameters chosen for analysis for these specimens. Therefore, the results lacked confidence and were purposely not listed in Table 3.

A similar copper wire and resin system for superconductor applications was studied and showed similar anisotropy [13]. In that case, due to the small sample cross section area (about 15 mm × 15 mm), the TPS method could not be used to generate results without the interference of physical boundaries of the samples.

While the relatively large specimen thickness used with the TPS method and its sensor potentially allows for the achievement of statistical homogeneity, in which the same large thickness also inherently introduces complications associated with the transfer of the planar heating and its interpretations. If these complications could be resolved somehow, then the TPS method perhaps eventually could be used to estimate κ_app with the achievement of statistical homogeneity.

3.2.5 Thermal Transmittance Response. The κ_app perpendicular to the wires was insensitive to specimen thickness for the transmittance test method. The amount of scatter in their measurements was also arguably equivalent and independent of the specimen thickness.

This test method was found to be unsuitable for measuring κ_app parallel to the wires. The thermal interface between the apparatus and the sample comprised the majority of the measurement and could not be predicted with sufficient repeatability to extract meaningful results for the sample.

The specimen thickness range, ∼3.2 to −6.4 mm, is smaller than the ∼ 10 to 15 L (or ten diameters of copper wire) size, so it is probable that a RVE of these packed copper wire coupons was not achieved with them. If thinner specimens could have been fabricated for this test method, then their scatter would be expected to be larger. If thicker test specimens could have produced accurate κ_app measurements, then less scatter would be expected.

3.2.6 Modeled Apparent Thermal Conductivity. Two approaches were developed to model the tested samples and estimate the thermal conductivity in the direction of greater interest—the perpendicular apparent thermal conductivity. One was a FEA thermal model for the wire bundle that was previously applied in Ref. [14] that expands on the technique of proposed by Kanzaki et al. [15] for closed (hexagonal) patterned wire bundles. The FEA model is a RVE that adds the wire insulation component to the bare wire and fill materials. In addition, the FEA accounts for 2D heat transfer effects not accounted for in the Kanzaki model. The second followed a method described by Kanzaki et al. [9], which is a 2-dimensional analytical method that models the RVE as an integrated sum of differential width parallel thermal resistances for open (square) patterned wire bundles.

3.2.6.1. Finite element analysis. The measured thermal transmittance results for perpendicular κ_app are compared to the FEA-predicted response in Fig. 7, and they show the measured κ_app values were slightly higher than those predicted by the FEA. The fill factor was determined for each individual sample tested using the density and image-analysis methods. The image analysis method yielded higher and more variable fill factor results than the density method due to variation in sample edges. Variation in fill factor measured by image-analysis caused the fluctuation in κ_app for the FEA high result shown in Fig. 7(*a*).

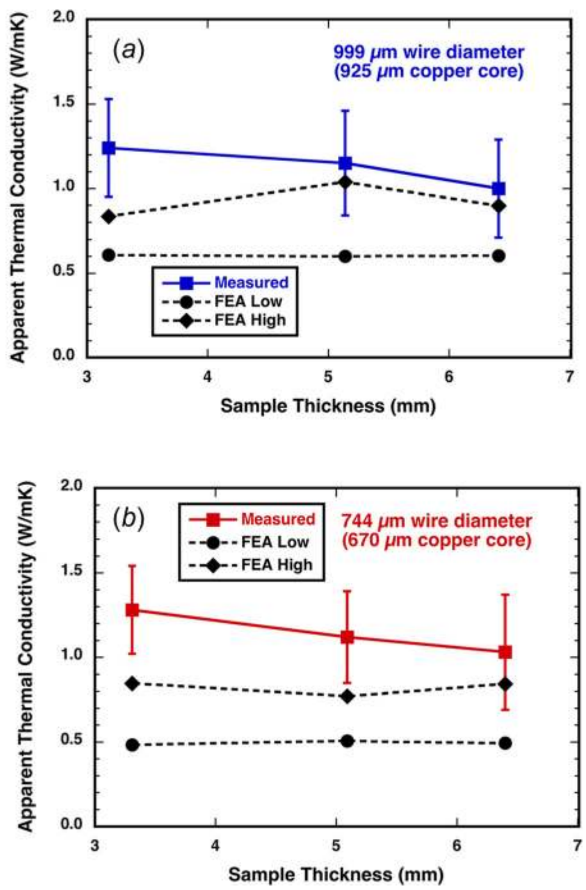

Fig. 7 Apparent thermal conductivity perpendicular to wires as a function of sample thickness using transmittance test method for (*a*) 925-μm-diameter or 19-Ga and (*b*) 670-μm-diameter or 22-Ga copper core wires. Indicated bars on the measurements represent 95% confidence bands. FEA low and high bounds represent fill-factors from density and image analysis estimations, respectively.

[3]The test instrument's software tries to optimize the test parameters by minimizing the temperature rise and measurement time. There are warnings when the temperature is too high (above 3 °C) or the measurement time is too long or too short (calculated from the diffusivity of the sample and the diffusion depth). In the case of a 2W-10 second combination, an introduced higher temperature resulted so this condition was not examined here.

The results for the two methods bound the κ_app FEA predictions in Fig. 7. Uncertainty was determined with the 95% confidence interval including all known random and systematic sources of error [16].

An unanticipated trend exists in Fig. 7 that deserves interpretation, namely, the measured κ_app values are larger than the predicted values. The FEA modeling assumes ideal close- or hexagonal-packing, ideal varnish fill, and no thermal interfacial losses among the constituents. In reality, none of those assumptions are satisfied. Given those assumptions and existence of pores, the measured κ_app would be expected to be lower than the predicted values.

Evidence of percolation channels existed in the sectioned packed-copper wire samples, see Fig. 8, and their presence could have produced measured k_app values larger than the (idealized) predicted k_app values shown in Fig. 7. Such percolation channels show the copper-wire-spacing is not perfectly uniform throughout the volume of the packed-copper wires; in other words, their existence is more likely as the average wire packing fraction becomes higher and higher. Their channels are comprised of adjacent copper wires that are locally and inhomogeneously packed close to one another. Their relatively close proximity provides preferential pathways or "short circuits" for thermal transfer, and their net effect is to produce a higher-valued thermal conductivity measurement of the entire volume than for the same volume that homogeneously spaced wires (i.e., no percolation channels). Models such as Kanzaki's [9] or Simpson et al. [17] do not address this issue, but it arguably is a realistic phenomenon that could readily occur in copper-wire-packing applications like that shown in Fig. 2.

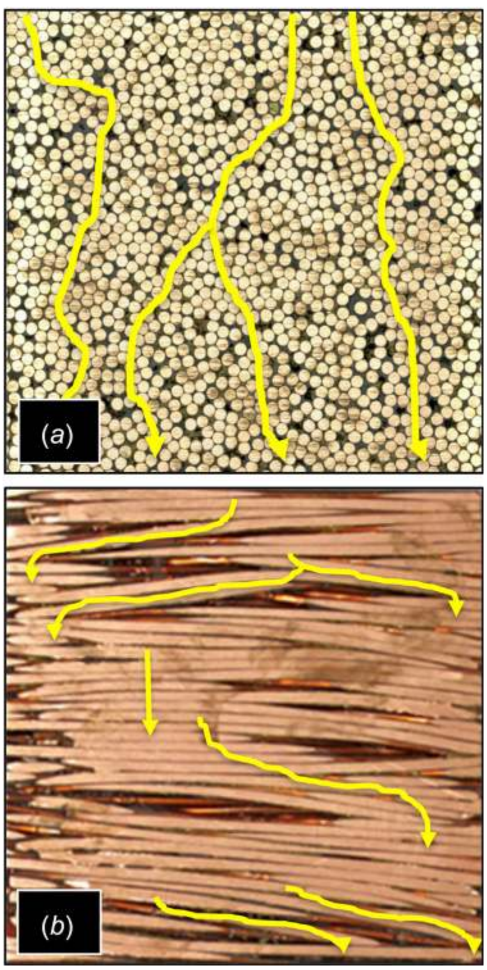

Fig. 8 Percolation pathways that potentially provide localized, preferential thermal conduction. Potential pathways are illustrated for two mutually orthogonal sections of packed-copper wire.

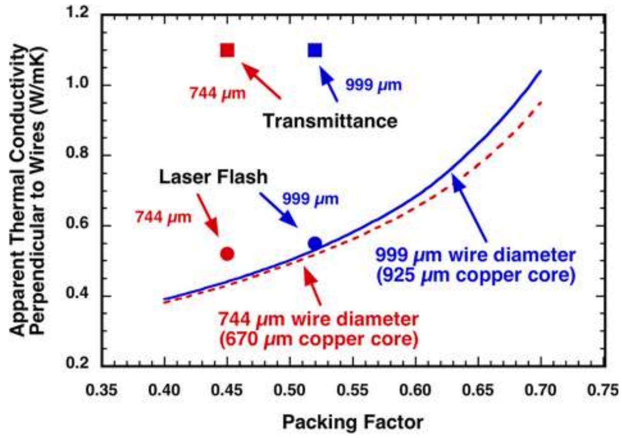

Fig. 9 Predicted apparent thermal conductivity as a function of packing efficiency (after Kanzaki et al. [9]) for the two examined wire diameters compared to measured responses

3.2.6.2 Kanzaki numerical analysis. The Kanzaki model provides a satisfactory numerical estimation of the κ_app of the packed copper wire in the direction perpendicular to the oriented wires. This estimation attractively takes into account the wire diameter and its κ, wire-insulation coating thickness and its κ, and the packing factor and the κ of the interstices material. One of its advantages is that simple numerical methods (using spreadsheet analysis) can be employed to conduct its analysis (i.e., FEA not required).

Key assumptions of the Kanzaki method are the same as those for the FEA analysis and include consistent wire spacing, open or square pattern of wires, and ideal varnish fill. The difference is the FEA uses closed pack wire pattern while the Kanzaki method uses open pack or square wire pattern. It is possible to extend the method to a closed wire pattern; however, including an insulation layer in the closed wire pattern with the model can become numerically cumbersome.

The Kanzaki method does not account for preference of heat flow through the copper components. As a result, the method tends to underestimate apparent thermal conductivity by 25–30% compared to the FEA prediction; however, if the k_app of a wire-

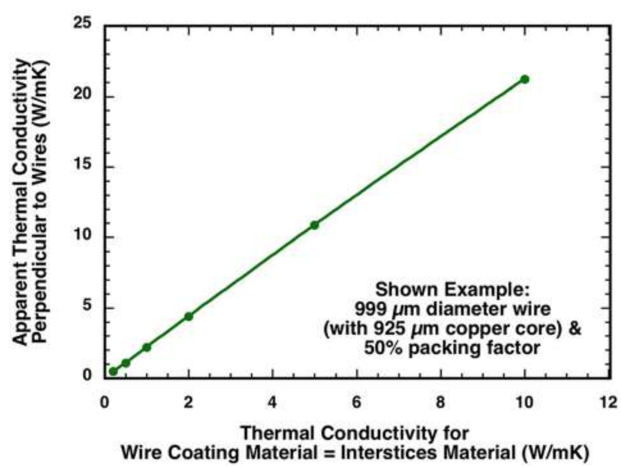

Fig. 10 Calculated apparent thermal conductivity perpendicular to the wires as a function of thermal conductivity of the wire-coating material and interstices material (after Kanzaki et al. [9]). The thermal conductivities of the wire-coating and interstices material are set equal in this example.

packed configuration is only on the order of 1 W/mK (i.e., an already-existing thermally *insulative* condition), then that underestimation in the Kanzaki method is arguably not significant in the overall thermal transfer within it.

The Kanzaki model also estimates a predicted κ_app that is less than the measured response, see Fig. 9. Similar to the FEA prediction, this underestimation is believed to be due to the experimental thermal conductivity percolation referred to in Fig. 8. Additionally, it supports the existing expectations that increasing the κ of both the wire-insulating coating material and the material in the interstices can significantly increase the κ_app perpendicular to the wire orientation in packs of copper wire. This is illustrated by the example shown in Fig. 10, and it shows that κ_app perpendicular to packed copper wire can significantly increase by increasing the thermal conductivities of the wire coating and interstitial materials by arguably modest amounts.

4 Summary and Conclusions

- The apparent thermal conductivity, k_app, of the packed copper wire was approximately two orders of magnitude higher in the direction parallel to the wires than perpendicular to them. The former was over 200 W/mK while the latter was only 0.5–1 W/mK for a wire packing efficiency of approximately 50%.
- The anisotropic apparent thermal conductivity of packed copper wire can be satisfactorily estimated with appropriate specimen preparation and their use with the laser flash and transmittance test methods. The transient hot disk method did not consistently produce trustworthy and defendable apparent thermal conductivity results for these specimens and their architecture.
- The measured apparent thermal conductivity responses of the packed copper wires consisting of either 670- or 925-μm-diameter wires did not exhibit significant differences in the direction perpendicular to the wires at a packing efficiency of ~50%. The Kanzaki model's prediction of apparent thermal conductivity differences for their combinations also indicates an equivalence. However, the apparent thermal conductivity parallel to the wires for the 925-μm-diameter-containing wires was nearly 10% higher than that for the wire packs containing the 670-μm-diameter wires.
- The average apparent thermal conductivity perpendicular to the wires and the amount of scatter was insensitive to specimen thickness (for thicknesses 3.2–6.4 mm) for the transmittance test method. It is believed this thickness range constitutes a size smaller than the representative volume element for these packed copper wire systems; therefore, the amount of scatter in the measured apparent thermal conductivity could be greater and less as the thickness gets smaller and larger, respectively.
- Percolation channels, representing localized pathways having relatively high concentrations of copper, likely caused the packed copper wire to have a slightly higher apparent thermal conductivity than that predicted by FEA.
- The Kanzaki model (with FEA confirmation):
  - Provides a satisfactory numerical estimation of the apparent thermal conductivity of the packed copper wire in the direction perpendicular to the oriented wires. This estimation attractively takes into account the wire diameter and its thermal conductivity, wire-insulation coating thickness and its thermal conductivity, and the packing factor and the thermal conductivity of the interstices material.
  - Supports the expectations that increasing the thermal conductivity of both the wire-insulating coating material and the material in the interstices can significantly increase the apparent thermal conductivity perpendicular to the wire orientation in packs of aligned copper wire.

Acknowledgment

Research co-sponsored by the Propulsion Materials Program and the Electric Drive Technologies Programs, DOE Vehicle Technologies Office, under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. The authors thank USDOE's J. Gibbs and S. Rogers, ORNL's J. A. Haynes and B. Ozpineci, and NREL's S. Narumanchi for their financial and managerial support, ORNL's R. Parten, S. Waters, and M. Modugno for their technical support, and ORNL's J. A. Haynes, J. Pries, T. R. Watkins and NREL's S. Narumanchi for reviewing the manuscript. This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan.[4]

Abbreviations and Symbols

ASTM = American Society for Testing and Materials
cm = centimeter or 10^{-2} m
Cp = heat capacity or specific heat
Cu = copper
FEA = finite element analysis
g = gram
Ga = gauge
HDTCA = hot disk thermal constants analyzer
in = inch or 0.0254 m
ISO = International Standards Organization
J = Joule
K = Kelvin
kg = kilogram
LLC = limited liability corporation
L = characteristic length or lineal dimension
m = meter
mm = millimeter or 10^{-3} m
MS = mail stop
NEMA = National Electrical Manufacturers Association
NREL = National Renewable Energy Laboratory
ORNL = Oak Ridge National Laboratory
RVE = representative volume element
s = second
SiC = silicon carbide
TPS = transient plane source
USDOE = United States Department of Energy
UT = University of Tennessee
W = watt
α = thermal diffusivity
κ = thermal conductivity
κ_app = apparent thermal conductivity
κ_para = parallel or axial thermal conductivity; one of two components of k_app using the TPS method
κ_perp = perpendicular or transverse thermal conductivity; one of two components of k_app using the TPS method
μm = micrometer or 10^{-6} m
ρ = density
°C = Celsius
⦸ = diameter

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