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PREDICTION OF THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF POROUS METALLIC MATERIALS*

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Abstract—Thermal conductivity and electrical resistivity of porous materials, including 304L stainless steel Rigimesh, 304L stainless steel sintered spherical powders, and OFHC sintered spherical powders at different porosities and temperatures are reported and correlated. It was found that the thermal conductivity and electrical resistivity can be related to the solid material properties and the porosity of the porous matrix regardless of the matrix structure. It was also found that the modified Wiedemann–Franz–Lorenz relationship is valid for the porous materials under consideration. For high conductivity materials, the Lorenz function and the lattice component of conductivity depend on the material and are independent of the porosity. For low conductivity, the lattice component depends on the porosity as well.

NOMENCLATURE

b,	constant in Wiedemann–Franz–Lorenz equation [$\text{Wm}^{-1}\ \text{K}^{-1}$];
C_0, C_1,	constants, equation (9);
L,	constant in Wiedemann–Franz–Lorenz equation [$\text{V}^2\ \text{K}^{-2}$];
n,	constant, equation (3);
T,	temperature [K];
α,	temperature coefficient for conductivity, equation (11) [K^{-1}];
β,	temperature coefficient for resistivity, equation (12) [K^{-1}];
λ,	thermal conductivity [$\text{Wm}^{-1}\ \text{K}^{-1}$];
ρ,	electrical resistivity [Ωm];
ξ,	porosity.

Subscript

0,	solid material ($\xi = 0$).

INTRODUCTION

THERMAL conductivity of porous material is an important property in determining the temperature distribution of coolant and of the porous structure in transpiration cooling. Due to the irregularity of the microstructure, confident calculation of the theoretical thermal conductivity of porous material is rather difficult if not impossible. Existing prediction methods are based on certain simplifications; such as, parallel cylinders, laminates in series, spheres dispersed in a conducting medium, etc. Even with a well defined microstructure, the problem remains complex due to the existence of the interface resistance. Therefore, with the exception of parallel cylinders, a semi-empirical approach is the only practical way of confidently

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Table 1. *Thermal conductivity*, ($W\ m^{-1}\ K^{-1}$), *and electrical resistivity* (Ωm) *of porous materials*

(a) 304L stainless steel Rigimesh

Porosity	0·093		0·203		0·385	
Temperature (K)	λ	$10^8\rho$	λ	$10^8\rho$	λ	$10^8\rho$
373	13·7	100	8·6	159	4·3	327
573	16·2	117	10·1	187	5·1	384
773	18·9	130	11·6	208·5	5·8	424
973	21·5	140·5	13·0	225	6·55	451
1173	24·2	148·5	14·4	237·5	7·3	478
1273	25·4	152	15·2	243	7·6	492

(b) 304L stainless steel sintered powders

Porosity	0		0·0924		0·215		0·315	
Temperature (K)	λ_0	$10^8\rho_0$	λ	$10^8\rho$	λ	$10^8\rho$	λ	$10^8\rho$
373	16·3	78·8	11·9	112	9·1	147·5	5·5	250
573	18·9	93·0	14·0	122	10·2	175	6·5	291
773	21·75	104·5	16·0	135	11·4	195	7·6	315
973	24·5	112·0	18·2	146	12·6	213	8·6	332
1173	27·3	116·5	20·4	157	13·7	231	9·6	338

(c) Oxygen free high conductivity copper sintered powders

Porosity	0		0·103		0·210		0·304	
Temperature (K)	λ_0	$10^8\rho_0$	λ	$10^8\rho$	λ	$10^8\rho$	λ	$10^8\rho$
373	396	2·30	324	2·85	232	4·25	163	6·2
473	389	3·00	315	3·70	221	5·6	158	7·9
573	380	3·70	307	4·55	207	7·3	154	9·8
673	370	4·45	297·5	5·40	197	9·0	148	11·8
873	360	5·20	289	6·4	184	11·15	143	13·7
973	351	6·02	280	7·4	172	13·1	139	15·7
1073	342	6·9	271	8·75	160	15·1	—	17·7

predicting the thermal conductivity of porous materials. This approach was used by Grootenhuis, Powell and Tye [1] who measured the thermal conductivity and electrical resistivity of sintered bronze powder at several values of porosity from 293 K to 473 K. They found that all the data on thermal conductivity λ and electrical resistivity ρ at different temperatures T may be represented by a straight line given by equation (1).

$$\lambda = 2{\cdot}43 \times 10^{-8}\frac{T}{\rho} + 2{\cdot}1. \qquad (1)$$

For thermal conductivity calculations of porous bronze, they suggested the use of the following equation:

$$\frac{\lambda}{\lambda_0} = 1 - 2{\cdot}1\xi \qquad (2)$$

where λ_0 is the thermal conductivity of solid material.

Recently, Aivazov and Domashnev [2] derived an expression for the thermal conductivity of porous materials as follows:

$$\frac{\lambda}{\lambda_0} = \frac{1 - \xi}{1 + n\xi^2} \qquad (3)$$

where n is an experimentally determined constant.

The purpose of the present study is (1) to provide experimental data of thermal conductivity and electrical resistivity of different porous materials over a temperature range from 373 K to 1273 K, and (2) to develop semi-empirical equations for the prediction of thermal conductivity, electrical resistivity, and their interrelationship from these data. The porous materials studied are (1) 304L stainless steel woven wire, (2) 304L stainless steel sintered spherical-powder, and (3) oxygen-free high conductivity copper sintered spherical-powder. For convenience, these materials will be called Rigimesh, stainless powders and copper powders respectively in this paper. Three different porosities of each material are investigated. A detailed description of porous material microstructure, dimension of specimens, and method of measurements are reported in [3–6].

THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY

The thermal conductivity and electrical resistivity for Rigimesh, stainless steel powders and copper powders are shown in Table 1 (a), (b) and (c), respectively. Using the thermal conductivity and electrical resistivity of solid material as a reference, the dimensionless thermal conductivity λ/λ_0 and the dimensionless electrical resistivity ρ_0/ρ can be computed. It was found that both λ/λ_0 and ρ_0/ρ are insensitive to temperature. The mean values of these two quantities as a function of porosity are shown in Table 2 and Fig. 1. The solid lines in Fig. 1

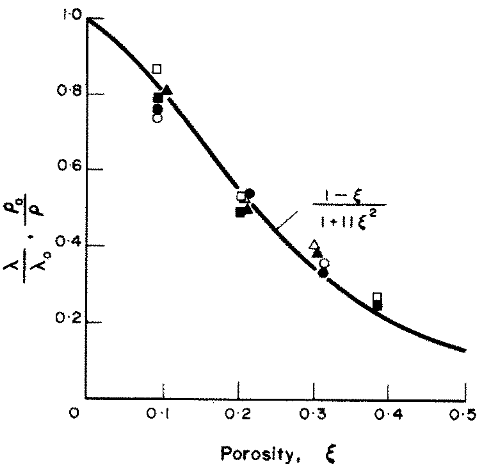

FIG. 1. Dimensionless thermal conductivity, λ/λ_0 and dimensionless electrical resistivity, ρ_0/ρ of porous materials.

	$\frac{\lambda}{\lambda_0}$	$\frac{\rho_0}{\rho}$
304 L SS Rigimesh	□	■
304 L SS powders	○	●
OFHC Cu powders	△	▲

Table 2. Dimensionless conductivity and resistivity

Materials	Porosities	λ/λ_0	ρ_0/ρ
304L SS	0·093	0·869	0·790
Rigimesh	0·203	0·530	0·494
	0·385	0·267	0·243
304L SS	0·0924	0·739	0·750
Sintered powders	0·215	0·528	0·526
	0·315	0·347	0·330
OFHC	0·103	0·805	0·810
Sintered powders	0·210	0·528	0·494
	0·304	0·403	0·380

are represented by a correlation discussed in the following section.

CORRELATION OF DIMENSIONLESS CONDUCTIVITY AND RESISTIVITY

Different correlation equations have been published in the literature [1, 2, 7–12]. The present experimental data can be represented best by equation (3). It was deduced for a porous material having a number of different pore configurations [2].

Using the results in Table 1, it was found by statistical analysis that the mean value of n is 11; therefore, the dimensionless conductivity is given by the following:

$$\frac{\lambda}{\lambda_0} = \frac{1-\xi}{1+11\xi^2}. \tag{4}$$

Equation (4) yields a good correlation for all experimental data (see Fig. 2). However, it should be noted that n is sensitive to (1) the manufacturing characteristics of porous material, (2) the contamination of material associated with the sintering process, and (3) the accuracy of the porosity, conductivity, and resistivity measurements. Similarly, the correlation of electrical resistivity is given by:

$$\frac{\rho_0}{\rho} = \frac{1-\xi}{1+11\xi^2}. \tag{5}$$

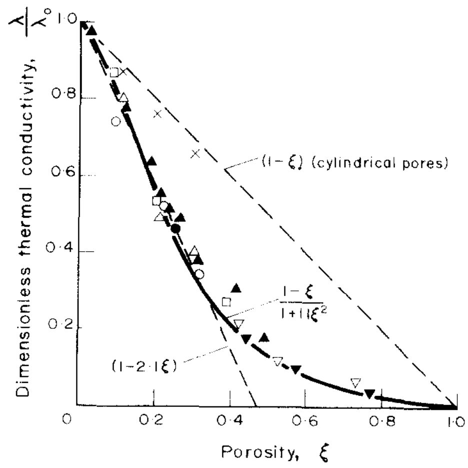

FIG. 2. Comparison of experimental data and correlations of thermal conductivity of porous materials.

□	304 LSS Rigimesh
○	304 LSS Powders
△	OFHC Cu Powders
×	Al_2O_3, Cylindrical Pores (12)
▲	Al_2O_3, (14)
▽	Foametal, (15)
▼	Feltmetal, (15)
●	Porous 301 SS, (16)

Equations (4) and (5) are shown as solid lines in Fig. 1. Considering the complexity of the problem and the significant differences in microstructures from Rigimesh to sintered powders, it is concluded from Fig. 1 that the correlation is satisfactory.

Other correlations and experimental data

It was shown in [1] that for sintered matrices, the experimental data on thermal conductivity can be correlated best by a simple straight line given in equation (2).

An extensive review of literature on thermal conductivity of porous materials performed in [13] shows that equation (2) indeed represents such experimental data as well. This correlation, together with equation (4) and the model of parallel cylinders, are shown in Fig. 2. Some experimental data are also shown in the figure for comparison. For clarity, the experimental data for sintered powders compiled in [1, 13] are not shown in this figure.

Figure 2 shows that the equation

$$\frac{\lambda}{\lambda_0} = \frac{1 - \xi}{1 + 11\xi^2}$$

correlates all the experimental data very well. On the other hand, the parallel cylinder model, $\lambda/\lambda_0 = 1 - \xi$ would overestimate the conductivity while the correlation $\lambda/\lambda_0 = 1 - 2{\cdot}1\xi$ would underestimate the conductivity when the porosity is larger than 0·30.

Figure 2 shows also that the conductivity for Foametal and Feltmetal at high porosity ($\xi \geqslant 0{\cdot}42$) can be represented by equation (4). No experimental data for these materials at low porosities are available to substantiate the correlation.

RELATION BETWEEN THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY

Relation established in literature

Published literature [17] shows that within the temperature range where there is no magnetic transformation the thermal conductivity and electrical resistivity of solid materials are approximately related by the following equation which is based upon the Wiedemann–Franz–Lorenz law.

$$\lambda_0 = L\frac{T}{\rho_0} + b \qquad (6)$$

where L = Lorenz function

$\frac{LT}{\rho_0}$ = electronic component of thermal conductivity

b = lattice component of thermal conductivity.

Values of L and b for different materials can be found in [17].

λ vs T/ρ of present data

Using the results in Table 1, the functional relationship between λ and T/ρ for the present data is shown in Figs. 3–5 for the stainless

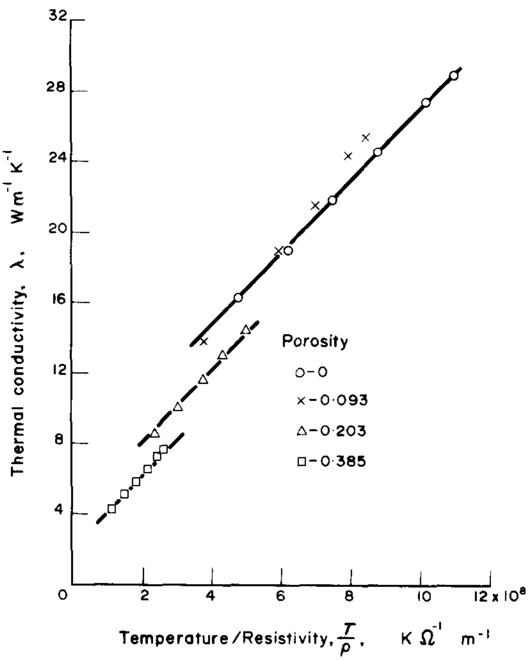

FIG. 3. Thermal conductivity vs temperature/resistivity of porous 304L stainless steel Rigimesh.

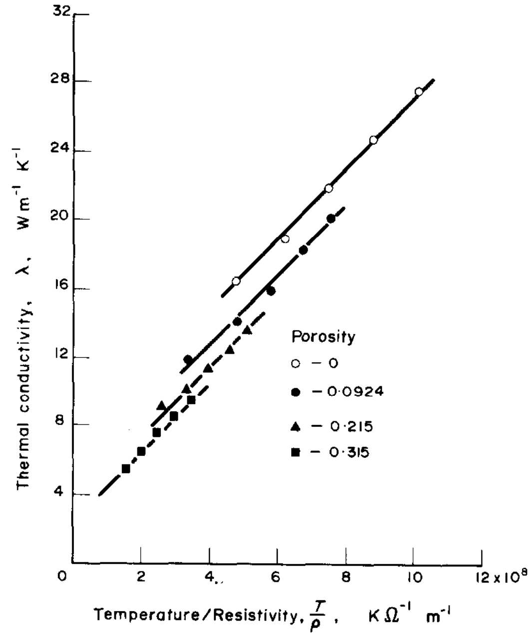

FIG. 4. Thermal conductivity vs temperature/resistivity of 304L stainless steel sintered powders.

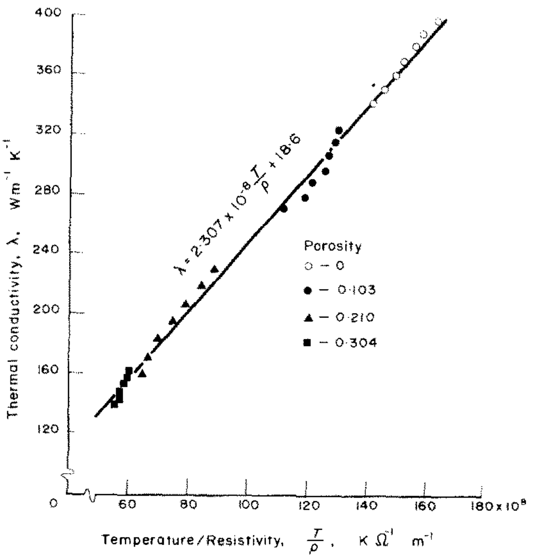

FIG. 5. Thermal conductivity vs temperature/resistivity of OFHC sintered powders.

steel Rigimesh, stainless steel powders, and copper powders respectively. For the stainless steel materials, Figs. 3 and 4 show that distinct straight lines could be drawn through the data for each porosity. The slope is essentially the same between different lines and thus independent of porosity. Therefore, for the stainless steel materials, the Lorenz function in equation (6) is indeed a constant independent of porosity, while the lattice component of conductivity b depends on the porosity. For the copper material, Fig. 5 shows that all the data can be essentially represented by a single line independent of porosity. Using a least square method, the line which represents best the experimental data is as follows:

$$\lambda = 2{\cdot}307 \times 10^{-8}\frac{T}{\rho} + 18{\cdot}6 \text{ (copper powders).} \tag{7}$$

In [1], it is shown that the thermal conductivity and electrical resistivity of bronze powders can be represented by the following relation independent of porosity.

$$\lambda = 2{\cdot}43 \times 10^{-8}\frac{T}{\rho} + 2{\cdot}1 \text{ (bronze powders).} \tag{8}$$

So far, the available experimental data for porous materials show that:

(1) The relation given by equation (6) is valid.
(2) The Lorenz function L depends on the kind of material and is independent of porosity.
(3) The lattice component of conductivity b depends on the kind of material for bronze and copper. It depends on the porosity as well for the stainless steel.

Experimental results [18] show that for porous bronze and copper, the lattice component of thermal conductivity is relatively unimportant (up to 14 per cent of total conductivity), while for porous stainless steel Rigimesh the lattice component of conduction (38 per cent) is almost as important as the electronic component of conduction. Therefore, it is appropriate to postulate that within the temperature range where there is no magnetic transformation the lattice component of conduction depends on the porosity and temperature for all the materials. But, due to the limit in experimental accuracy, the effect of porosity on the lattice component of conductivity can only be found in low conductivity materials where the lattice conductivity is important and cannot be found in high conductivity materials were the lattice conductivity is relatively unimportant. The experimental difficulty also precludes the determination of temperature effects on the lattice component of conductivity. For engineering applications, it may be stated that for bronze and higher conductivity materials, the thermal conductivity and resistivity is related by a single line of equation (6) with a single slope L and a single intercept b independent of porosity. For stainless steel and low conductivity materials, the thermal conductivity and electrical resistivity is related by a set of straight lines.

Correlation of λ vs T/ρ *for* 304*L stainless steel*

The experimental data on thermal conductivity and electrical resistivity at different temperatures and porosities are correlated to a single equation by the following postulations:

(1) The slope L in equation (6) is a constant independent of porosity.

(2) The lattice component of conductivity b is a linear function of porosity, i.e.

$$b = C_0 - C_1\xi.$$

Thus, equation (6) can be rewritten as

$$\lambda = L\frac{T}{\rho} + C_0 - C_1\xi. \tag{9}$$

The constants, L, C_0 and C_1 are found by the following steps:

(1) For each porosity, determine the best slope L by a least squares method.

(2) All the values of L found in Step (1) are added and divided by the number of porosities. The result is taken as the best value for L.

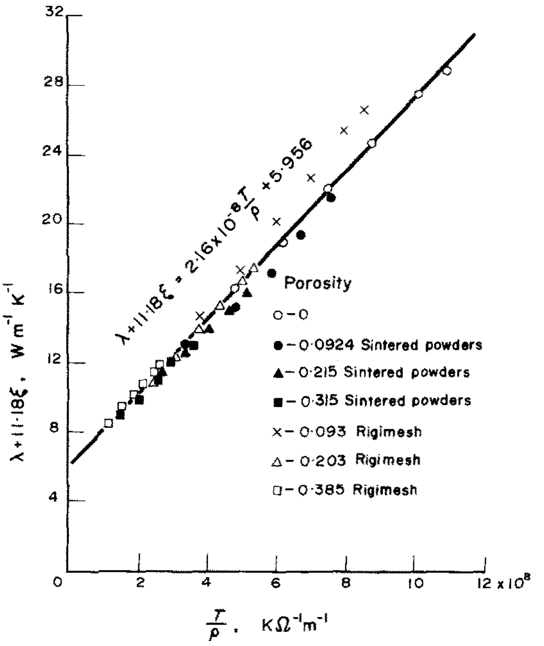

FIG. 6. Correlation of thermal conductivity, λ, electrical resistivity ρ, porosity ξ, and temperature T, of 304L stainless steel Rigimesh and powders.

(3) Using the best value of L in equation (9) and the experimental data of λ, T/ρ and ξ, the best values of C_0 and C_1 are determined by a least squares method.

The resulting equation as found by the foregoing procedure for the 304L stainless steel Rigimesh and powders is as follows:

$$\lambda + 11{\cdot}18\xi = 2{\cdot}16 \times 10^{-8}\frac{T}{\rho} + 5{\cdot}956. \tag{10}$$

This correlation is shown in Fig. 6 together with the experimental data. The maximum deviation between the correlation line and the experimental data is 9 per cent for the Rigimesh at 0·093 porosity. Over 70 per cent of the data falls within 5 per cent of the value given by equation (10). In view of the complexity of the problem, this correlation is deemed satisfactory.

TEMPERATURE EFFECTS

Using the thermal conductivity and electrical resistivity at 373 K as a reference, the thermal conductivity and electrical resistivity at any temperature T (K) may be computed by the following equations:

$$\frac{\lambda_T}{\lambda_{373}} = 1 + \alpha\,(T - 373) \tag{11}$$

$$\frac{\rho_T}{\rho_{373}} = 1 + \beta\,(T - 373). \tag{12}$$

The coefficients α and β are essentially independent of porosity and have the following numerical values [18] valid for a temperature range from 373 K to 1273 K.

$$\alpha = \begin{cases} 0{\cdot}00089\ \mathrm{K}^{-1} & \text{stainless steel} \\ 0{\cdot}000265\ \mathrm{K}^{-1} & \text{copper} \end{cases} \tag{13}$$

$$\beta = \begin{cases} 0{\cdot}000544\ \mathrm{K}^{-1} & \text{stainless steel} \\ 0{\cdot}00329\ \mathrm{K}^{-1} & \text{copper.} \end{cases} \tag{14}$$

PREDICTION OF THERMAL CONDUCTIVITY OF POROUS MATERIALS

In general, the thermal conductivity and electrical resistivity of a solid material can be found in the literature. This information may be used to estimate the thermal conductivity of the material at different porosity and temperature by the following procedure:

Porous material conductivity computed from solid conductivity information

When the thermal conductivity of solid material is known, the thermal conductivity of porous material can be computed by use of equation (4) at corresponding temperatures. When the thermal conductivity of solid material is known only at a certain temperature, the thermal conductivity of porous material at any other temperature may be found by first computing the solid material conductivity at the porous material temperature by use of an equation similar to equation (11) and then obtaining the answer by use of equation (4).

Porous material conductivity computed from resistivity data

When the electrical resistivity of a solid material as a function of temperature is given, the thermal conductivity of porous material can be found by two steps:

(1) Determine the thermal conductivity of solid material as a function of temperature by use of equation (6) with appropriate constants L and b.

(2) Compute the thermal conductivity of porous material by use of equation (4).

When the electrical resistivity of a solid material is known at a temperature only, the thermal conductivity at the same temperature can be found by use of equation (6). Equation (11) can then be used to determine the solid conductivity at any other temperature. Finally, the thermal conductivity of the material at a specific porosity can be computed by use of equation (4).

CONCLUSIONS

Thermal conductivity and electrical resistivity of stainless steel Rigimesh, stainless steel sintered powders, and copper sintered spherical-powders at different porosities have been measured over a temperature range from 373 K to 1273 K. Data have been analyzed and correlated. The correlations were tested using existing data for other porous materials. Based on this study, the following conclusions may be drawn:

(1) For sintered powders and Rigimesh, the dimensionless thermal conductivity can be represented by

$$\frac{\lambda}{\lambda_0} = \frac{1 - \xi}{1 + 11\xi^2}$$

and the dimensionless electrical resistivity by

$$\frac{\rho_0}{\rho} = \frac{1 - \xi}{1 + 11\xi^2}.$$

The thermal conductivity correlation also fits the existing data on thermal conductivity of foametal, feltmetal, and non-spherical sintered powders.

(2) Within the temperature range where there is no magnetic transformation, the thermal conductivity of porous metals is related to the electrical resistivity and temperature by the equation: $\lambda = (LT/\rho) + b$. For a high conductivity material, such as bronze and copper where the lattice component of conduction is relatively unimportant, the slope L and the intercept b are a function of material but independent of porosity. For a low conductivity material, such as stainless steel where the lattice component of conductivity is almost as important as the electronic component of conductivity, this intercept depends on the porosity as well.

(3) The thermal conductivity of porous materials can be computed from the information of solid material thermal conductivity and/or electrical resistivity.

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DETERMINATION DE LA CONDUCTIVITE THERMIQUE ET DE LA RESISTIVITE ELECTRIQUE DE MATERIAUX METALLIQUES POREUX

Résumé—On rapporte et met en relation la conductivité thermique et la résistivité électrique de matériaux poreux, comprenant l'acier inoxydable 304 L Rigimesh, des poudres sphériques frittées d'acier inoxyable 304 L et des poudres sphériques frittées OFHC pour différentes porosités et températures. On a trouvé que la conductivité thermique et la résistivité électrique peuvent être reliées aux propriétés du matériau solide et à la porosité de la matrice poreuse indépendamment de la structure de la matrice. On a également trouvé que la relation modifiée de Wiedemann–Franz–Lorenz est valable pour les matériaux poreux considérés. Pour des matériaux à haute conductivité la fonction de Lorenz et la composante du réseau de conductivité dépendent du matériau et sont indépendantes de la porosité. Pour une faible conductivité la composante du réseau dépend de la porosité.

BESTIMMUNGEN DER WÄRMELEITFÄHIGKEIT UND DES ELEKTRISCHEN WIDERSTANDES PORÖSER METALLISCHER STOFFE

Zusammenfassung—Es wird über die Wärmeleitfähigkeit und den elektrischen Widerstand poröser Materialien bei verschiedenen Porositäten und Temperaturen berichtet. Rostfreier Rigimesh-Stahl 304 L und OFHC gesinterte Kugelpulver wurden ebenfals untersucht. Es zeigte sich, dass die Wärmeleitfähigkeit und der elektrische Widerstand auf die Eigenschaften des festen Stoffes und die Porosität der porösen Matrix bezogen werden können, unter Vernachlässigung der Matrixstruktur. Ausserdem ergab sich, dass die modifizierte Wiedemann–Franz–Lorenz-Beziehung für die betrachteten Stoffe gültig ist. Für Stoffe mit hoher Leitfähigkeit hängen die Lorenz-Funktion und die Gitterkomponente der Leitfähigkeit nur vom Stoff ab und sind unabhängig von der Porosität. Bei geringer Leitfähigkeit hängt die Gitterkomponente ausserdem von der Porosität ab.

РАСЧЕТ КОЭФФИЦИЕНТОВ ТЕПЛОПРОВОДНОСТИ И ЭЛЕКТРИЧЕСКОГО СОПРОТИВЛЕНИЯ ПОРИСТЫХ МЕТАЛЛИЧЕСКИХ МАТЕРИАЛОВ

Аннотация—Представлены значения коэффициентов теплопроводности и электрического сопротивления пористых материалов, изготовленных из сфериуеских порошков нержавеющей стали 304 *Л* и сферических порошков OFHC с различной пористостью и при различных температурах. Найдено, что коэффициенты теплопроводности и электрического сопротивления зависят от характеристик твердых материалов и пористости пористой матрицы и не зависят от структуьы матрицы. Найдено также, что модифицированное соотношение Видеманна-Франца-Доренца справедливо для рассматриваемых пористых материалов. Для материалов с высоким коэффициентом теплопроводности функция Лоренца и теплопроводность, обусловленная кристаллической решеткой, зависят от материала и не зависят от пористости. Для материалов с низким коэффициентом теплопроводности теплопроводность, обусловленная кристаллической решеткой, зависит также и от пористости.