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# THERMAL CONDUCTANCE OF ALUMINA–NICKEL INTERFACES AT ELEVATED TEMPERATURES*

LANCE G. HAYS†

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

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**Abstract**—The thermal conductance in vacua between an alumina surface at 1100C and a nickel surface at 55–90°C was determined experimentally over a range of contact pressures. The added resistance due to a mono-layer of zirconia microspheres between these surfaces was also measured. The results show the predicted dependency of conductance upon contact pressure, but the absolute magnitudes were from $\frac{1}{2}$ to $\frac{1}{7}$ of the theoretical magnitudes.

## NOMENCLATURE

| | |
|---|---|
| $c$, | average spacing of contact points [cm]; |
| $k_s$, | thermal conductivity of material [W/cm°C]; |
| $k_{sm}$, | average thermal conductivity [W/cm°C]; |
| $p$, | contact pressure [N/cm$^2$]; |
| $u$, | thermal conductance [W/cm$^2$°C]; |
| $\sigma$, | indentation hardness [N/cm$^2$]. |

Subscripts

| | |
|---|---|
| 1, | alumina property; |
| 2, | nickel property. |

## 1. INTRODUCTION

THERMAL insulation of the field structure and electrical coils from a high-temperature, high-velocity fluid steam is required in all magnetohydrodynamic (MHD) generators. The insulating media should be electrically non-conductive, of minimum thickness, and resistant to corrosion from the high-velocity, high-temperature fluid.

An insulation system, suitable for an 1100C liquid–metal MHD system [1] was conceived which utilizes the contact resistance between ceramic and metal members to inhibit the heat flow. The conductance must be known to determine the cooling requirements of the generator in order to maintain a given temperature. Examination of the literature showed the most applicable work on contact heat transfer to be that of Rapier *et al.* [2] who determined values of conductance for uranium-dioxide–stainless-steel interfaces at temperatures to 400C. Their results gave values of less than 0·05 W/cm$^2$°C for conductance for some surface combinations which, if valid for the higher temperature and different materials of this application, would produce acceptably low values of 50 W/cm$^2$ or less for heat flux.

An experiment was carried out to measure the thermal conductance of an alumina–nickel interface at 1100C in order to obtain information that would be directly applicable to design of the MHD generator. In addition, the effect of inserting a mono-layer of ceramic microspheres between the ceramic–metal interface was measured. This latter experiment was

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† Senior Research Engineer.

performed to determine if the heat transfer could be further reduced with a modest penalty in spacing.

## 2. THEORETICAL RELATION FOR CONDUCTANCE

The problem of heat flow through contact spots between two surfaces in vacua has been treated in the past and is discussed by Rapier *et al.* [2]. A result which they reproduce from others [3, 4] follows from two main assumptions:

1. The material plastically deforms until the total area of the contact spots, times the indentation hardness of the softer material, equals the loading force.
2. The resistance to heat flow is due to the constriction effect on flow lines resulting from the small contact spots. The assumption is made that the contact spots are circular and the heat is drawn from larger, cylindrical cells in the material.

With these assumptions, the relation for thermal conductance for the case of $p \ll \sigma$ is:

$$u_{12} = \frac{k_{sm}}{c} \frac{p}{\sigma} \tag{1}$$

where

$$\frac{2}{k_{sm}} = \frac{1}{k_{s1}} + \frac{1}{k_{s2}}. \tag{2}$$

The spacing, $c$, to be used in equation (1) is the larger of the two surfaces, and the indentation hardness, $\sigma$, is for the softer substance.

The major uncertainty in the use of equation (1) for surfaces with microscopic irregularities is the proper value of indentation hardness to used. Since all peaks are not at the same height, only a fraction will actually make contact. Thus, estimates of $c$ from surface profile measurements, which do not measure true height or flatness, may not be meaningful. Another uncertainty is the proper value of indentation hardness to use for the microscopic case. Surface treatment and/or reactions may give values quite different than the bulk material value as determined by an indentor.

## 3. EXPERIMENTAL APPARATUS

The surface combination of alumina to nickel was tested. Both surfaces were formed by lapping the flat end of a cylindrical test piece to an optical flatness to ensure uniform contact. Surface profile measurements of the alumina and nickel (after treatment with No. 320 grit alumina paper) are summarized in Fig. 1. Both surfaces were tested with optical blocks and were found to be flat to within one wavelength over the entire contact area.

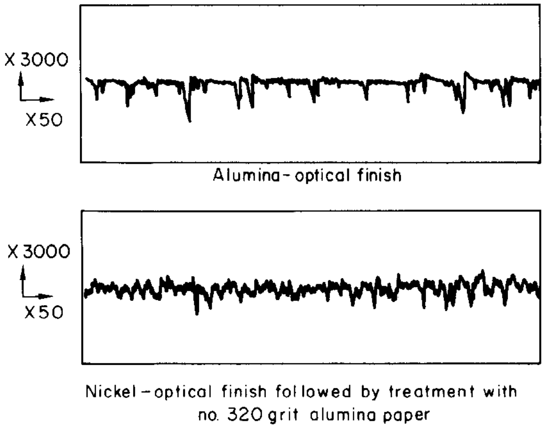

FIG. 1. Surface profile of alumina and nickel test surfaces.

The alumina was joined (before lapping) by brazing, to a niobium–1% zirconium body. The niobium alloy body was used to contain the heating source and to transmit loads to the interface. A schematic of the test setup is shown in Fig. 2. The heat was applied by an electron beam heating element inserted within the niobium body. The entire heated assembly was insulated by wrapping with 20 layers of dimpled tantalum foil for radiation shielding. The nickel base had internal water cooling to remove the heat transferred across the test surfaces. The surface temperature was maintained at 55–90C over the range of heat fluxes by this method.

The test pieces were assembled in a diffusion-pumped vacuum chamber as shown in Fig. 2. The nickel base was stationary while the alumina–niobium unit was free to translate. Load was applied to the stem in the vertical direction through an "O" ring and bellows seal which allowed free movement of the test piece. The surfaces were outgassed in the separated position before applying a load in all but one test sequence. During the tests, the pressure in the chamber was between $2 \times 10^{-5}$ and $5 \times 10^{-6}$ torr, virtually eliminating gas conduction effects between the surfaces.

Temperature measurement was accomplished with an optical pyrometer and chromel–alumel thermocouples. The pyrometer was sighted on a hohlraum with a length-to-diameter ratio of two, that was drilled into the side of the alumina test surface. Heat flux was determined by measuring the cooling water flow rate and inlet and outlet temperatures. The loading force was measured by a bonded strain gauge force transducer. The force due to ambient pressure acting on the area of the bellows vacuum seal was 12·5 N (2·8 lb). This value was added to the measured load to determine the total force acting on the 1 cm$^2$ contact area.

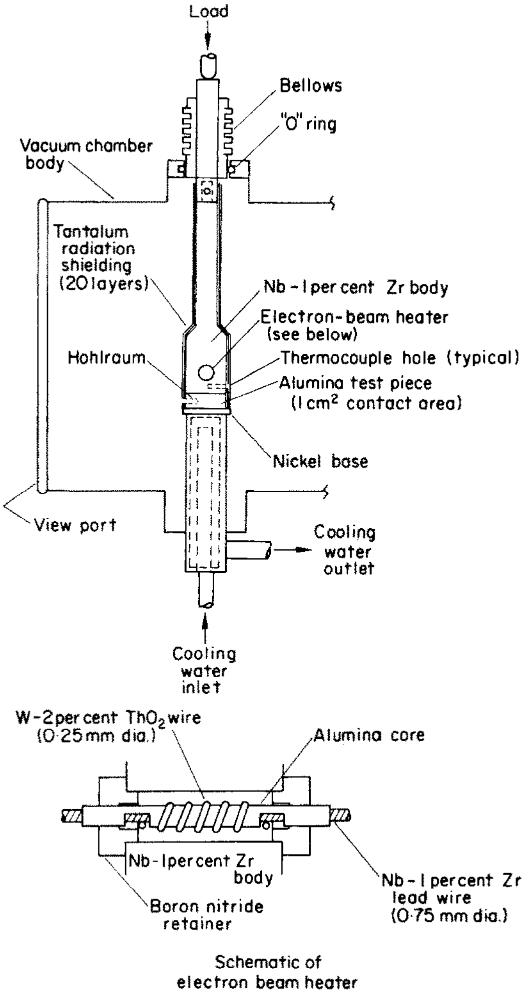

FIG. 2. Contact heat-transfer test section.

### 4. EXPERIMENTAL RESULTS

The total heat transfer coefficient at 1100C alumina temperature is shown as a function of contact pressure for three different surface combinations in Fig. 3. The optically lapped surfaces varied between 0·004 W/cm$^2$ °C at a contact pressure of zero (radiant heat transfer with a 0·5 mm spacing) and a value of 0·046 W/cm$^2$ °C at a contact pressure of 82·6 N/cm$^2$, the maximum tested. The values obtained after the nickel was dressed with a No. 320 grit alumina paper are somewhat higher than the optical finish. This result was probably the consequence of the removal of a surface oxide

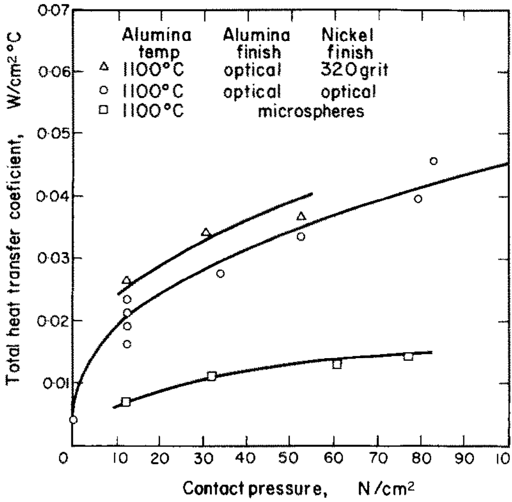

FIG. 3. Contact heat transfer from alumina at 1100°C to nickel at 55–90°C vs. contact pressure for different surfaces.

film which was produced by a chemical cleaning operation. The value of thermal conductance for the alumina-roughened surface combination at 52·5 N/cm$^2$ contact pressure was compared to the calculated conductance using equation (1) and an average value of $c$ from Fig. 1. The following values were used for the parameters of equation (1):

$k_{s1} = 0\cdot052$ W/cm°C [5]
$k_{s2} = 0\cdot865$ W/cm°C [6]
$c_2 = 0\cdot00933$ cm (Fig. 3)
$\sigma_2 = 0\cdot828 \times 10^5$ N/cm$^2$ [7]
$p = 52\cdot5$ N/cm$^2$.

With these numerical values, the calculated conductance is $u_{12} = 0\cdot277$ W/cm$^2$ °C. This value is about 7 times larger than the measured value of 0·037 W/cm$^2$ °C at this contact pressure.

A comparison of the calculated values with the experimental values shows that somewhat closer agreement exists. At the contact pressure of 60·6 N/cm$^2$, the calculated value was 0·0264 W/cm$^2$ °C and the experimental value was 0·0130 W/cm$^2$ °C. Once again the deviation is probably due to the fact that all the spheres do not make contact with the surface.

Although the absolute magnitude of the experimental values was different from those calculated for the heat-transfer coefficient, the trend with contact pressure is in agreement. When the conductance (corrected for radiation) for the two lapped surfaces was plotted vs. contact pressure on a logarithmatic scale, the best fit was provided by an equation of the form $u =$ (constant) $p^{\frac{1}{2}}$, in agreement with equation (1).

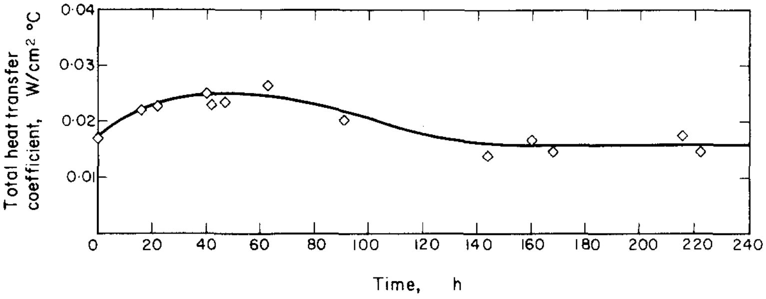

FIG. 4. Contact heat transfer vs. time with zirconia microspheres between alumina at 1100°C and nickel at 60–75°C; coefficient normalized to 48 N/cm$^2$ contact pressure.

However, the agreement with theory is improved when macroscopic contact elements were inserted. The lower curve of Fig. 3 was obtained with zirconia microspheres inserted between the alumina and nickel surfaces. The size of the microspheres ranged from 73 to 140 μm with an average size of 107 μm. The technique resulted in a marked reduction in heat transfer. For example, at the contact pressure of 41·3 N/cm$^2$ the heat-transfer coefficient was reduced from a maximum of 0·036 W/cm$^2$ °C to 0·012 W/cm$^2$ °C.

The stability of the microspheres as an insulation over a period of time was determined, and the results are summarized in Fig. 4. The total heat transfer coefficient normalized to 48·2 N/cm$^2$ is plotted vs. time with the alumina at 1100°C. The coefficient rose from an initial value of 0·017 W/cm$^2$ °C to a maximum of 0·026 W/cm$^2$ °C and thereafter declined to a steady-state value of about 0·015 W/cm$^2$ °C. The initial rise may have been the result of out-gassing since the surfaces were in contact before evacuation in this test sequence.

## 5. CONCLUSIONS

The contact resistance to heat transfer between two surfaces has been shown to be an effective, high-temperature insulation means for MHD generators. Experiments have shown coefficients of less than 0·040 W/cm$^2$ °C to result for contact of high-temperature alumina on cooled nickel at contact pressures of 50 N/cm$^2$. Insertion of a mono-layer of $\sim$100/μm zirconia microspheres further reduced the coefficient to 0·015 W/cm$^2$ °C at the same contact pressure. The resistance to heat transfer was found to be stable for a period of greater than 200 h at 1100C. Calculated values for conductance were higher than measured values, probably due to variations in the height of microscopic peaks and the macroscopic spheres. However, the conductance was found to be proportional to the square root of the contact pressure, which is in agreement with theory.

## ACKNOWLEDGEMENTS

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## CONDUCTANCE THERMIQUE D'INTERFACES ALUMINE/NICKEL À DES TEMPÉRATURES ÉLEVÉES

**Résumé**—La conductance thermique dans le vide entre une surface d'alumine à 1100°C et une surface de nickel à 55–90°C a été déterminée expérimentalement dans une gamme de pressions de contact. La résistance additionnelle due à une monocouche de microsphères de zircone entre ces surfaces a été aussi mesurée. Les résultats montrent la dépendence prédite de la conductance sur la pression de contact, mais les grandeurs absolues étaient de $\frac{1}{2}$ à $\frac{1}{7}$ des grandeurs théoriques.

## THERMISCHER KONTAKTWIDERSTAND EINER ALUMINIUM–NICKEL-PAARUNG BEI HÖHEREN TEMPERATUREN

**Zusammenfassung**—Der thermische Kontaktwiderstand zwischen einer Aluminium-Oberfläche von 1100°C und einer Nickel-Oberfläche von 55–90°C wurde im Vakuum experimentell für einen Bereich verschiedener Anpressdrücke bestimmt. Der zusätzliche Widerstand infolge einer Monoschicht aus Zirkonmikrokügelchen zwischen den Flächen wurde ebenfalls gemessen. Die Ergebnisse zeigen die vorhergesagte Abhängigkeit des Widerstandes vom Anpressdruck, die absoluten Werte betrugen jedoch nur $\frac{1}{2}$ bis $\frac{1}{7}$ der theoretischen Werte.

## ТЕПЛОПРОВОДНОСТЬ ПОВЕРХНОСТИ РАЗДЕЛА КОРУНД-НИКЕЛЬ ПРИ ВЫСОКИХ ТЕМПЕРАТУРАХ

**Аннотация**—Экспериментально определялась теплопроводность вакуума между поверхностью алюминия при 1100°C и поверхностью никеля при 55–90°C в диапазоне контактных давлений. Измерялось также добавочное термическое сопротивление, обусловленное наличием монослоя микросфер циркония между этими поверхностями. Результаты подтвердили полученную расчетным путем зависимость теплопроводности от контактного давления, но абсолютные величины составляли от $\frac{1}{2}$ до $\frac{1}{7}$ теоретических значений.