Int. J. Heat Mass Transfer. Vol. 29, No. 8, pp. 1103–1108, 1986
Printed in Great Britain

0017-9310/86 $3.00+0.00
Pergamon Journals Ltd.

Thermal conductance at solid interfaces: an application of the Fenech–Rohsenow model

HENRI FENECH
Department of Chemical and Nuclear Engineering, University of California, Santa Barbara, CA 93110, U.S.A.

Abstract—An analysis of the thermal conductance of 240 pairs of uranium dioxide–Zircaloy-4 contact is presented. The analysis uses the Fenech–Rohsenow (F–R) model and the surface profiles obtained from mass-produced UO_2 pellets and Zircaloy cladding used in nuclear reactor fuel assemblies. For no contact pressure the differences in surface finish and the relative position of the surfaces in contact give a wide range of thermal contact conductance from 1.14 to 3.60 W cm^{-2} $°C^{-1}$ in a helium environment. The contact conductance is insensitive to contact pressure up to 0.7 MPa apparent pressure. The values of the thermal conductance increase rapidly beyond that pressure due to the plastic flow of the Zircaloy-4 surface asperities. Values of thermal contact conductance evaluated with the Ross and Stoute (R–S) correlation are higher than those obtained with the F–R correlation. This difference is attributed to the use of average fluid thickness in the R–S correlation.

1. INTRODUCTION

THE THERMAL contact resistance at solid interfaces has been recognized in heat transfer equipment design for several decades. Early predictions of the contact resistance were obtained from experiments specifically applicable to the nature of the contact considered: Weills and Ryder [1], Brunot and Buckland [2] and Barzelay *et al.* [3, 4]. The analytical and experimental work of Centinkale and Fishenden [5] published in 1951 pointed to a novel and more fundamental approach to the study of the thermal contact resistance of solid interfaces. Direct analytical solution proved impractical because of the many boundary conditions. An explicit expression for the contact conductance was developed by the relaxation method, which does not account for the surface profiles and the number and size of contact points.

A research program was initiated by W. M. Rohsenow at MIT in 1954 on thermal contact conductance. This program was active for some 10 years and significantly contributed to the fundamental understanding and analytical capability in that field. Three doctoral students and eight master degree candidates participated in this effort. The Fenech–Rohsenow (F–R) correlation [6] for thermal conductance of solid interfaces was one of the early accomplishments of this project. The same geometrical model as Cetinkale and Fishenden's was used. The heat diffusion equation was resolved explicitly by satisfying 'averaged' boundary conditions. The expression for the contact conductance considered the detailed profile of the surfaces in contact for the determination of the contact point density and of the average gap thickness between the solids. A brief review of that correlation is given in the Appendix. The model was thoroughly and successfully tested on specimens representing the ideal geometry used for the analysis, on pyramidal asperities pressed against optical flat and on sandblasted surfaces. Air, water and mercury were used successively for the interfacial fluid [7]. Kaszubinski [8] performed an experimental verification of the overlapping surface profiles graphical methods for the determination of the contact point density. The autoradiographic technique consisted of activating a molecular layer of gold deposited on one surface and photographically analyzing the number of radioactive points transferred on the second surface after placing the two solids in contact under a broad range of pressure up to 7×10^4 kPa. To overcome the complexity of the graphical determination of the contact points density and average fluid thickness, Henry [9] developed an analog computer and software to conveniently analyze the contacting surface profiles. Subsequently, several workers in that field derived simpler or semi-empirical formulations currently used in industry which are more limited in application: Mikić [10], Ross and Stoute [11], Rapier *et al.* [12] and Yovanovich [13]. The F–R model, however, remains very useful for accurate and fundamental analytical work on contact conductance. Some typical studies made using the F–R method include: the effects of vibration on thermal contact resistance [14]; the determination of the thermal contact resistance of graphite [15]; the contact conductance of graphite and thorium oxide matrix [16]; and application to crystalline materials contact [17]. This paper presents one of the latest applications of the F–R method for the determination of the inherent variations of closed-gap conductance in nuclear fuel pins. The study examines the spread in contact conductance between uranium dioxide (UO_2) fuel pellets and Zircaloy-4 cladding in a helium environment. The spread is due to the variations in the pellets and cladding surface conditions obtained in a mass production plant and to the uncontrollable relative position of the two surfaces in contact. An experimental evaluation of these effects would involve a very costly and time-consuming program. The random experimental errors in the measurements of the gap conductance would, in addition, cause variations which are not clearly separable from the random effects of the surface conditions.

2. ANALYSIS OF CLOSED-GAP CONDUCTANCE FOR URANIUM DIOXIDE–ZIRCALOY-4 CONTACT IN HELIUM

Sixty Zircaloy-4 cladding and 60 UO_2 pellets were randomly selected from a lot of 120 claddings and 100 pellets supplied by a nuclear fuel manufacturer. In addition, two pairs of UO_2–cladding combination were selected to give a match of the smoothest and roughest contact. The surfaces of all the cladding and pellets were recorded in the longitudinal and circumferential directions and stored in digital format on magnetic tape for further processing. Up to 2600 data points were used to record the profile of each surface over a 12-mm length.

The analysis of the gap conductance using the F–R method (described in the Appendix) was performed with a computer code 'MESURCO' developed by Barroyer [18]. This program reads from the data banks of the profiles of the two surfaces in contact in the axial and circumferential direcions. The pellet profiles are inverted and placed in contact with their associated cladding profiles. A translation and rotation of the pellet profiles is performed to establish two contact points on each pair of profiles corresponding to a zero contact pressure. An increase in contact pressure is simulated by the pellet profile displacement into the cladding profile. The effects of different positioning of the solid interfaces was obtained by a lateral displacement of one metal surface profile with respect to the other surface profile. All the parameters (average void thickness–average peak height, contact point density, etc.) are then computed and the gap conduction is calculated.

For each of the 60 pairs of UO_2–Zircaloy-4 contact, four cases were executed.

(a) Profiles in their initial relative position and zero contact pressure.
(b) Pellet profiles translated to the left by 0.160 mm (6.25×10^{-3} in.) and zero contact pressure.
(c) Profile in their initial relative position followed by a translation of the pellet surface into the clad surface by 1.27×10^{-4} mm (5×10^{-6} in.), corresponding to a positive contact pressure ranging from 70 Pa (10^{-2} p.s.i.) to 13.80 MPa (2×10^3 p.s.i.)
(d) Same as case (b) followed by case (c), i.e. contact pressure increase by displacement of 1.27×10^{-4} mm.

The surface roughness (r.m.s.) and average peak heights of the pellets and inner surface cladding in the axial and circumferential directions are given in Table 1.

The physical properties used for this analysis correspond to a realistic nuclear fuel contact temperature of 482°C (900°F) at operating conditions.

Thermal conductivity:

Uranium dioxide	$K = 0.043\ \mathrm{W\ cm^{-1}\ {}^\circ C^{-1}}$
Zircaloy-4	$K = 0.171\ \mathrm{W\ cm^{-1}\ {}^\circ C^{-1}}$
Helium	$K = 0.0286\ \mathrm{W\ cm^{-1}\ {}^\circ C^{-1}}$

Zircaloy-4 yield pressure = 413.7 MPa

The correction term on the helium thermal conductivity for the radiation heat transfer at 482°C and the temperature jump due to energy accommodation at the gas–solid interface were determined to be negligible at the contact operating conditions.

3. RESULTS OF THE ANALYSIS

The 240 pairs of contact conductance data have been separated into two categories: gap conductance

Table 1. Surface characteristics of the pellets and cladding

	Surface roughness* [mm (r.m.s.)] Axial	Surface roughness* [mm (r.m.s.)] Circular	Average peak height† (mm) Axial	Average peak height† (mm) Circular
Pellets				
min	2.34×10^{-3}	4.42×10^{-3}	2.77×10^{-3}	1.36×10^{-3}
max	5.94×10^{-3}	1.78×10^{-3}	5.08×10^{-3}	3.22×10^{-3}
Cladding				
min	1.16×10^{-4}	2.69×10^{-4}	2.87×10^{-4}	5.6×10^{-5}
max	3.06×10^{-3}	3.81×10^{-3}	4.03×10^{-4}	2.84×10^{-3}

* The surface roughness is defined as $\left(\frac{1}{L}\int_0^L y^2\,dx\right)^{1/2}$ where y is the surface profile height from a median $0x$ axis corresponding to a zero average height.

† The average peak height is defined as $\frac{1}{L}\int_0^L |y|\,dx$.

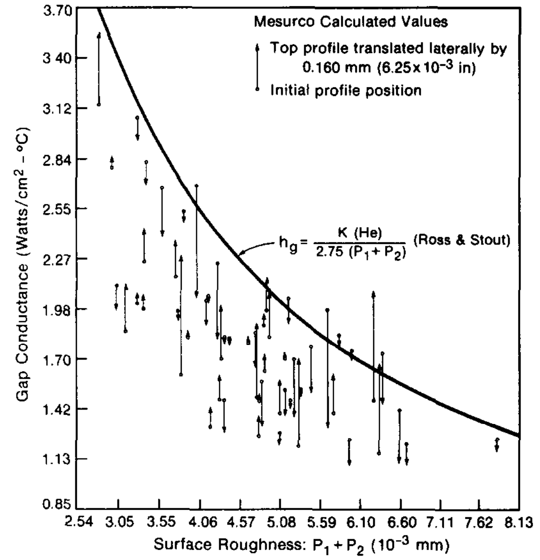

Fig. 1. Dependence of gap conductance on surface roughness at zero contact pressure.

for just contacting surfaces at zero pressure and gap conductance for a range of contact pressure (corresponding to a nominal 1.27×10^{-4} mm step of one surface into the other).

The gap conductance values for a zero contact pressure as a function of the two surfaces peak heights arithmetic average ($P_1 + P_2$) are plotted in Fig. 1. Two values are shown on this figure corresponding to initial and translated profiles. There is a wide spread in the surfaces' total peak arithmetic average (2.80×10^{-3} mm $< P_1 + P_2 < 7.85 \times 10^{-3}$ mm) corresponding to large variations of the gap conductance, ranging from 1.14 to 3.60 W cm^{-2} $°C^{-1}$. A small shift (0.160 mm) in the relative lateral position of the surfaces in contact causes large changes, mostly increases, in the gap conductance (up to 40%). These variations are physically possible because of the random meshing of the peaks and valleys on the matching surfaces. Of practical consideration in an operating nuclear reactor, when contact has been established between the pellet and the cladding, power changes causing relative motion of the pellet–cladding interface are likely to increase appreciably the contact conductance. This effect, however, is overshadowed by the surface roughness variations obtained with mass-produced pellets. It can also be observed from the data in Fig. 1 that the Ross and Stoute (R–S) correlation [11] overpredicts the gap conductance in almost all cases. The conjecture for this is that the R–S correlation is established on the basis of average peak heights. For zero contact pressure the interfacial fluid thickness, as determined by the F–R method, is set by the maximum peak heights which yield larger effective fluid thickness and, in the case of interfacial helium gas, lower gap conductance.

The cases of gap conductance with contact pressure include surfaces in contact with an in-step motion of 1.27×10^{-4} mm of one surface into the other followed by a lateral translation of 0.160 mm of the pellet surface. Some selected cases are shown in Fig. 2 where the conductance values for a single contact before and after the lateral motion are joined by a pointed line. The contact pressure used on this figure as variable was established from the contact area and the Meyer's hardness of Zircaloy-4 (413.7 MPa). The wide range of contact pressures from 7×10^{-4} to 14 MPa is due to the different relative configurations of the two profiles. For contact pressure up to 0.7 MPa, the gap conductance values remain pressure insensitive and in general are in the range 1.14–2.28 W cm^{-2} $°C^{-1}$. The width of this range is mostly controlled by the surface roughness and to a lesser extent by the relative position of the surfaces in contact. Using the same values for the contact pressure, the R–S gap conductance was calculated and is plotted in Fig. 2. For the R–S

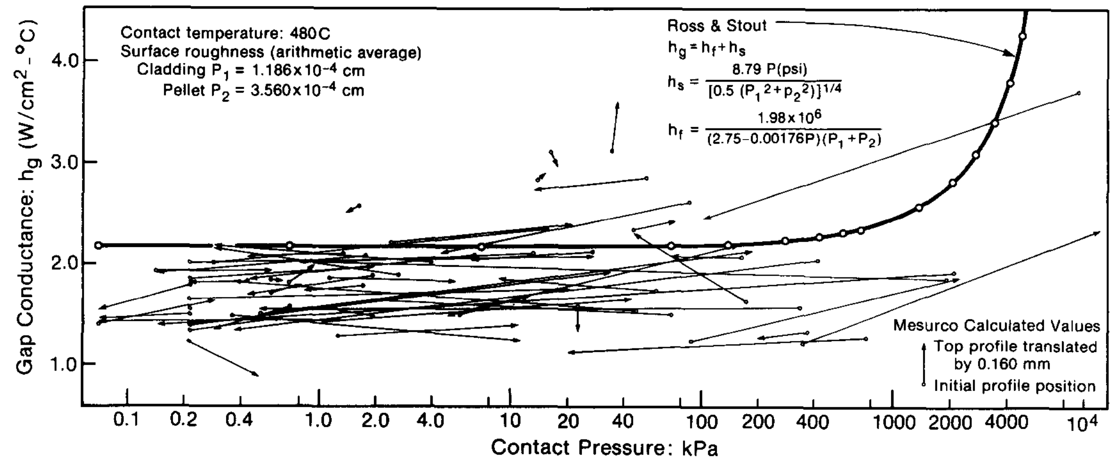

Fig. 2. Dependence of gap conductance on contact pressure and effect of surface configuration. (Ross and Stoute peak arithmetic average $P_1 + P_2 = 4.75 \times 10^{-3}$ mm.)

correlation, an average value for all the specimen of the peak height arithmetic average of the cladding ($P_1 = 1.186 \times 10^{-3}$ mm) and of the pellets ($P_2 = 3.56 \times 10^{-3}$ mm) was used. The R–S correlation shows the same pressure trends as the F–R correlation but predicts higher values of the gap conductance (in some cases by as much as a factor of 2) in the low pressure range. This difference is also attributed to the underestimation of the effective interstitial fluid thickness through the use of arithmetic average values and to the empirical form of the R–S correlation, which lacks parameters describing the surface profiles in contact.

4. CONCLUSION

The present study evaluates the effect of solid surface states on the thermal contact conductance. The Fenech–Rohsenow correlation used for this study to determine the general trends of surface profile effect on thermal contact provides useful observations that are difficult to obtain experimentally. The 240 cases of uranium dioxide–Zircaloy-4 contact in helium analyzed give widespread values of the thermal contact conductance at zero contact pressure due to differences in the manufactured surface profiles and random matching of the surfaces (1.13–3.50 W cm^{-2} $^\circ\text{C}^{-1}$). Up to 0.7 MPa contact pressure, the thermal conductance remains sensibly independent of pressure. A rapid increase of the gap conductance occurs when the softer material in contact experiences yield stress and plastic flow underlying the contact areas.

Acknowledgements—The author is grateful to Dr W. M. Rohsenow for his initiative, guidance and invaluable participation in the early stage of development in this area of research, and to the numerous students involved in the various phases of contact conductance work. Those major participants are listed in the references.

REFERENCES

1. N. D. Weills and E. A. Ryder, Thermal resistance measurements of joints formed between stationary metal surfaces, *Trans. Am. Soc. mech. Engrs* **71**, 259–267 (1949).
2. A. W. Brunot and F. F. Buckland, Thermal contact resistance of laminated and machined joints, *Trans. Am. Soc. mech. Engrs* **71**, 253–258 (1949).
3. M. E. Barzelay, K. N. Tong and G. F. Holloway, Effects of pressure on thermal conductance of contact joints, NACA Tech. Note 3295 (1955).
4. M. E. Barzelay, K. N. Tong and G. F. Holloway, Thermal conductance of contacts in aircraft joints, NACA Tech. Note 3167 (1954).
5. T. N. Cetinkale and M. Fishenden, Thermal conductance of metal surfaces in contact, *Int. Conference on Heat Transfer*, pp. 271–273. Institute of Mechanical Engineers, London (1951).
6. H. Fenech and W. M. Rohsenow, Prediction of thermal conductance of metallic surfaces in contact, *Trans. Am. Soc. mech. Engrs*, Series C, *J. Heat Transfer* **85**, 15–24 (1963).
7. H. Fenech, Thermal conductance of metallic surfaces in contact. Sc.D. thesis, Massachusetts Institute of Technology, Cambridge, MA (1959).
8. L. J. Kaszubinski, Determination of the number of contacts between two surfaces pressed together. S.M. thesis, Massachusetts Institute of Technology, Cambridge, MA (1962).
9. J. J. Henry and H. Fenech, The use of analog computers for determining surface parameters required for prediction of thermal contact resistance, ASME Heat Transfer Conference, paper No. 63-WA-104 (November 1963).
10. B. B. Mikić and W. M. Rohsenow, Thermal contact resistance, Mechanical Engineering Department Massachusetts Institute of Technology, Report No. DSR74542-41 (1966).
11. A. M. Ross and R. L. Stoute, Heat transfer coefficient between UO_2 and Zircaloy-2, AECL 1552, Atomic Energy of Canada, Ltd., Chalk River (1962).
12. A. C. Rapier, T. M. Jones and J. E. McIntosh, *Int. J. Heat Mass Transfer* **6**, 397 (1963).
13. M. M. Yovanovich and H. Fenech, Thermal contact conductance of nominally flat rough surfaces in a vacuum environment, AIAA 3rd Aerospace Science Meeting, Paper No. 66–42 (1966).
14. P. T. S. Choong, Vibration effects on thermal contact resistance. S.M. thesis, Massachusetts Institute of Technology, Cambridge, MA (1966).
15. S. S. Horn, Thermal contact resistance of graphite. S.M. thesis, Massachusetts Institute of Technology, Cambridge, MA (1963).
16. A. Muret, Thermal contact conductance of graphite and thorium oxide matrix. M.S. thesis, University of California, Santa Barbara, CA (1973).
17. W. M. Rohsenow, *Developments in Heat Transfer*, Chap. 13, 365–367. Massachusetts Institute of Technology Press, Cambridge, MA (1964).
18. P. M. R. Barroyer, Thermal conductance of metallic surfaces in contact. M.S. thesis, University of California, Santa Barbara, CA (1972).

APPENDIX

The analysis of solid interface contacts is made for an idealized cylindrical geometry shown on Fig. A1. The small

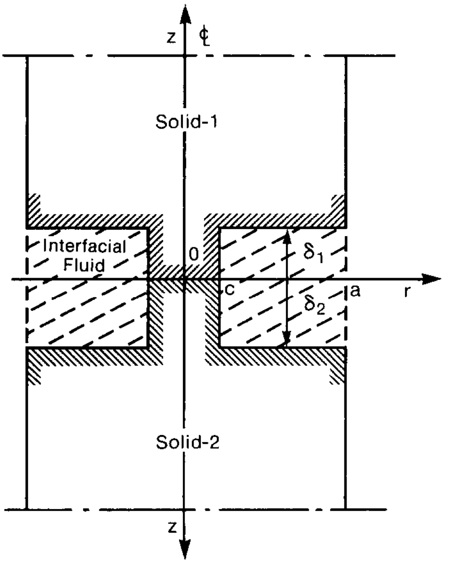

FIG. A1. Idealized contact geometry used in model analysis.

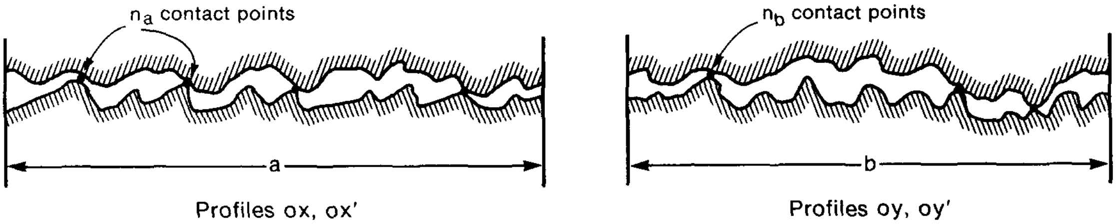

FIG. A2. Determination of the contact point density by profile meshing.

contact points are represented by short cylinders of radius c. The heat flow for a contact point is confined in a cylinder of radius a. The flow lines are 'pinched' through the contact area and a smaller heat flux is transferred by molecular conduction through the interstitial fluid of lower conductivity and thickness $\delta_1+\delta_2$.

An explicit solution of the diffusion equation without source term, $\nabla^2 T = 0$, is obtained by satisfying averaged boundary conditions. For example, the requirement of no heat loss in the radial direction at the boundary $r = a$ in the solid region is satisfied by the average boundary condition

$$\int_{\delta}^{\gamma} \frac{\partial T(z, r)}{\partial r}\,\mathrm{d}z = 0 \quad \text{at} \quad r = a. \tag{A1}$$

Explicit solutions of the temperature in all regions of the contact are obtained and used to determine the temperature drop, ΔT, caused by the contact by extrapolating the external solutions ($z \rightarrow +\infty$ and $z \rightarrow -\infty$) to $z = 0$.

The contact conductance h is thus obtained from the temperature gradient

$$\frac{\partial T(r, z)}{\partial z} \quad \text{at} \quad z = \infty$$

and the definition:

$$h = \frac{(Q/A)}{\Delta T} = -\frac{K}{\Delta T}\frac{\partial T(r, z)}{\partial z}\bigg|_{z=\infty}. \tag{A2}$$

This procedure yields the explicit form for the contact conductance:

$$\begin{aligned} h = \Bigg\{ & \frac{K_f}{\delta_1+\delta_2}\Bigg[(1-\varepsilon^2)\Bigg(\frac{4.26\sqrt{n}(\delta_1/\varepsilon)+1}{K_1} \\ & + \frac{4.26\sqrt{n}(\delta_2/\varepsilon)+1}{K_2}\Bigg) \\ & + 1.1\varepsilon f(\varepsilon)\left(\frac{1}{K_1}+\frac{1}{K_2}\right)\Bigg] + 4.26\varepsilon\sqrt{n}\Bigg\} \Bigg/ \\ & \times\left\{(1-\varepsilon^2)\left[1-\frac{K_f}{\delta_1+\delta_2}\left(\frac{\delta_1}{K_1}+\frac{\delta_2}{K_2}\right)\right]\right. \\ & \left.\times\left[\frac{4.26\sqrt{n}(\delta_1/\varepsilon)+1}{K_1}+\frac{4.26\sqrt{n}(\delta_2/\varepsilon)+1}{K_2}\right]\right\} \end{aligned} \tag{A.3}$$

where $\varepsilon^2 = A_c/A = Pa/H$ is the ratio of the contact area A_c over the total area A. The ratio is also equal to the ratio of the apparent contact pressure Pa and of the Meyer's hardness H of the softer solid. For most cases $\varepsilon < 0.1$ and $f(\varepsilon) \simeq 1.0$. n is the number of contact points per unit area of contact and is determined graphically from the number of interactions of two pairs of profiles obtained in perpendicular directions $0x$ and $0y$, as shown in Fig. A2

$$n = \frac{n_a n_b}{ab}. \tag{A4}$$

K_1, K_2 and K_f are the thermal conductivity coefficients of solids 1 and 2 in contact and of the interstitial fluids, respectively. The equivalent fluid thicknesses, δ_1 and δ_2, are determined to preserve the fluid volume associated with solids 1 and 2.

The above correlation, equation (A3), is applicable to flat surfaces with roughness only. When large contact surfaces are considered with several degrees of roughness and waviness, the overall contact conductance is obtained by the following recurrence formula:

$$\begin{aligned} h_n = \Bigg\{ & \frac{K_f}{\delta_{1,n}+\delta_{2,n}}\Bigg[(1-\varepsilon_n^2)\Bigg(\frac{2.4(\delta_{1,n}/c_n)+1}{K_1}+A_{n-1} \\ & + \frac{2.4(\delta_{2,n}/c_n)+1}{K_2}\Bigg) + 1.1\varepsilon_n f(\varepsilon_n)\left(\frac{1}{K_1}+\frac{1}{K_2}\right)\Bigg] + 2.4\frac{\varepsilon_n}{a_n}\Bigg\} \Bigg/ \\ & \times\left\{(1-\varepsilon_n^2)\left[1-\frac{K_f}{\delta_{1,n}+\delta_{2,n}}\left(\frac{\delta_{1,n}}{K_1}+\frac{\delta_{2,n}}{K_2}\right)\right]\right. \\ & \left.\times\left[\frac{2.4(\delta_{1,n}/c_n)+1}{K_1}+A_{n-1}+\frac{2.4(\delta_{2,n}/c_n)+1}{K_2}\right]+B_{n-1}\right\} \end{aligned} \tag{A5}$$

The analysis is implemented by recording n profiles obtained on the same surface by filtering the output of a profilometer for different frequency ranges covering the roughness and waviness characteristic frequencies. In the formulation

$$A_{n-1} = \frac{2.4/c_n}{h_{n-1}} \tag{A6}$$

$$B_{n-1} = \frac{1}{h_{n-1}}\left[1.1\varepsilon_n f(\varepsilon_n)\frac{K_f}{\delta_{1,n}+\delta_{2,n}}\left(\frac{1}{K_1}+\frac{1}{K_2}\right)+2.4\frac{\varepsilon_n}{a_n}\right] \tag{A.7}$$

h_{n-1} is the gap conductance obtained from the previous $(n-1)$ set of profiles, and the other symbols have the meaning defined previously where the additional subscript n denotes the order of recurrence.

CONDUCTANCE THERMIQUE AUX INTERFACES SOLIDES: UNE APPLICATION DU MODELE FENECH-ROHSENOW

Résumé—On présente une analyse de la conductance thermique de 240 paires de contact dioxyde d'uranium–Zircaloy 4. L'analyse utilise le modèle de Fenech–Rohsenow et les profils de surface obtenus à partir des boulets UO_2 et des gaines de Zircaloy utilisés dans les assemblages de combustible de réacteur nucléaire. En l'absence de pression de contact, les différences en finition de surface et en position relative des surfaces en contact donnent un large domaine de conductance thermique de contact depuis 1,14 jusqu'à 3,60 W/cm^2 C dans une ambiance d'hélium. La conductance de contact est insensible à la pression de contact jusqu'à 0,7 MPa. Les valeurs de conductance augmentent rapidement au delà de cette pression à cause de la déformation plastique des aspérités de la surface de Zircaloy 4. Des valeurs de la conductance de contact estimées avec la formule de Roos et Stoute sont plus élevées que celles obtenues avec la formule F–R. Cette différence est attribuée à l'emploi d'une épaisseur moyenne de fluide dans la formule R–S.

DER WÄRMELEITKOEFFIZIENT AN FESTEN GRENZFLÄCHEN: EINE ANWENDUNG DES FENECH-ROHSENOW-MODELLS

Zusammenfassung—Eine Untersuchung der Wärmeleitkoeffizienten von 240 Materialpaaren aus Urandioxid und Zircaloy-4 wird vorgestellt. Die Untersuchung benutzt das Fenech–Rohsenow-Modell, die Oberflächenprofile wurden von seriengefertigten UO_2-Tabletten und Zircaloy-Hüllrohren aufgenommen, die als Brennstäbe in Kernreaktoren eingesetzt werden. Wird kein Kontaktdruck aufgebracht, so erhält man durch die unterschiedliche Oberflächengüte und die relative Position der Verbindungsfläche zueinander eine große Streuung des Wärmeleitkoeffizienten zwischen 1,14 und 3,60 W cm^{-2} K^{-1} in Helium-Atmosphäre. Der Wärmeleitkoeffizient ist bis zu scheinbaren Drücken vom 0,7 MPa von Kontaktdruck unabhängig. Die Werte des Wärmeleitkoeffizienten steigen bei Überschreitung dieses Druckes aufgrund des plastischen Fließens der Zircaloy-4-Oberflächenunebenheiten stark an. Werte des Wärmeleitkoeffizienten, die mit der Ross–Stoute-Korrelation ermittelt werden, liegen höher als die Werte, die mit der F–R-Korrelation berechnet werden. Dieser Unterschied ist auf die Benutzung einer mittleren Fluiddicke in der R–S-Korrelation zurückzuführen.

ТЕПЛОПРОВОДНОСТЬ ТВЕРДЫХ ГРАНИЦ: ПРИМЕНЕНИЕ К МОДЕЛИ ФЕНЕХА-РОЗЕНАУ

Аннотация—Исследована теплопроводность 240 пар контактов двуокись урана-сплав циркалой-4. Использована модель Фенеха–Розенау и профили поверхности, полученные при массовом производстве шариков UO_2 и покрытия из сплава циркалой, применяемого в топливных узлах ядерных реакторов. При отсутствии контактного давления прекращаются изменения поверхности, а относительное положение поверхностей при контакте дает широкий диапазон для коэффициента контактной теплопроводности в гелиевом заполнителе от 1,14 до 3,60 Вт/см^{2}С. Контактная теплопроводность нечувствительна к контактному давлению вплоть до его значения 0,7 МПа. Теплопроводность быстро возрастает за пределами этого давления из-за перемещения неровностей поверхности сплава циркалой-4 вследствие течения. Значения контактной теплопроводности, определенные по зависимости Росса–Стоута, выше полученных по Ф–Р соотношению, что объясняется использованием средней толщины слоя жидкости в Р–С зависимости.