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AN EXPERIMENTAL STUDY OF HEAT TRANSFER THROUGH PERIODICALLY CONTACTING SURFACES

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Abstract—Experiments are described in which heat was transferred through the interface between two solids which were brought into contact and separated cyclically. The results showed that, despite large variations in thermal contact resistance from one meeting of the contact surfaces to the next, earlier theoretical work could be used to predict, with reasonable accuracy, the average thermal resistance arising from periodic interruption of the heat flow at the contact interface.

It was also found that a significant reduction in thermal resistance could be achieved by increasing the impact with which the surfaces made contact.

NOMENCLATURE

- f, frequency;
- $g[\ ]$, function of [ ];
- l_i, length of bar equivalent to the thermal resistance due to periodic interruption of heat flow;
- l_T, length of bar equivalent to the thermal resistance due to the combined effects of thermal contact resistance and periodic interruption of the heat flow;
- α, thermal diffusivity;
- λ, length of bar equivalent to half of the thermal contact resistance;
- τ_c, duration of time per cycle during which surfaces are in contact.

INTRODUCTION

AN ENGINEERING designer may have to estimate heat transfer through two solid surfaces which are alternately brought into contact and then separated in a continuous cycle.

The available information would probably include data on the thermal and mechanical properties, including hardness and surface profiles of the contacting materials; data on the interstitial fluid; the mean interface temperature; and the force holding the surfaces in contact. From this information an estimate could be made of the thermal resistance of the interface when in permanent contact [1–6]. The design problem is to estimate from this the expected average thermal resistance for the same surfaces when making intermittent contact, given the frequency and the proportion of the cycle time spent in contact.

The case considered here is that when the two surfaces are undergoing given cycles of contact and separation continuously; only the quasi-steady state is considered.

A theoretical study of an approximate representation of the problem was made by Howard and Sutton [7], who considered heat transfer in a mathematical model comprising two identical bars of material of length, l, whose longitudinal axes were in line and whose adjacent ends could be brought into contact and separated cyclically. The independent variables were frequency, f, of contact, proportion of the cycle time spent in contact, $(f\tau_c)$, thermal diffusivity, α, of the bar materials, bar length, l, and thermal contact resistance, R_c, of the interface; the dependent variable was the thermal resistance, R_i, due to periodic interruption of the heat flow at the contact interface. These thermal resistances were expressed as equivalent lengths of bar, 2λ and $2l_i$ respectively.

Dimensional analysis showed that for $(fl^2/\alpha) > 2.56\pi$

$$\left(\frac{fl_i^2}{\alpha}\right) = g\left[(f\tau_c), \left(\frac{f\lambda^2}{\alpha}\right)\right]. \tag{1}$$

A graph of equation (1) was presented.

EXPERIMENTAL WORK

Objectives

The object of the experimental work reported here was to ascertain how reality compares with theory, and to discover the effect on heat transfer of surface wear and the impact with which the surfaces came into contact.

Test rigs

Two test rigs were made. In principle, each consisted of two insulated metal bars whose adjacent ends could be brought into contact and separated cyclically. The remote end of one bar was heated while that of the other bar was cooled. The length of the bar, l_T, equivalent to the thermal resistance offered by the contact interface under all conditions was determined by extrapolation of the temperature distribution in each bar.

The first test rig was unsatisfactory because transverse heat flows could not be sufficiently well controlled by guard heaters.

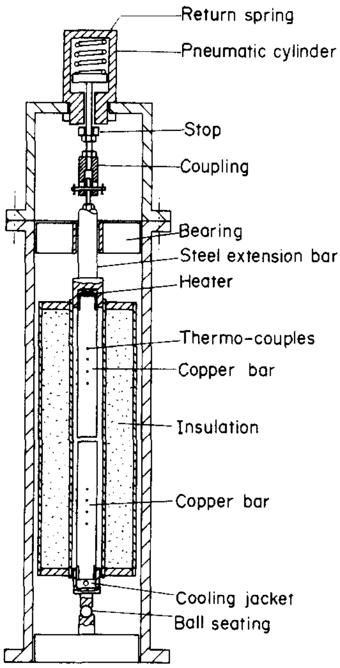

FIG. 1. Schematic drawing of test rig No. 2.

Figure 1 shows the second test rig schematically. Copper bars, 25.4 mm dia, 290 mm long were arranged vertically. When compressed air was supplied to the pneumatic cylinder at the top of the rig, the upper bar was lifted out of contact with the lower. When the air pressure was released, the upper bar fell under gravity and the return spring force until contact was re-established.

The frequency and proportion of the cycle time spent in contact were controlled by opening and closing valves in the inlet and exhaust air lines automatically.

A stabilised supply energised an electric heater which was fixed to the top of the upper bar. A cooling jacket was fitted to the lower end of the bar and supported on a ball seating, to allow the contact faces to seat squarely when in contact.

The bars were surrounded by a copper tube 32.4 mm bore, 35 mm O.D. fixed in firm contact with the extension bar securing the heater to the upper bar. The tube was free to slide over a collar surrounding the lower bar near the cooling jacket. The tube was surrounded by thermal insulation 76.2 mm O.D.

Instrumentation

Four chromel–alumel thermocouples made from 0.122 mm dia wire were installed on the axis of each bar as shown in Fig. 1, at the bottom of radial drillings and held in place with epoxy resin. Other thermocouples were in contact with the outer surface at the same axial positions and two further thermocouples were mounted in contact with the outer surface of each copper bar, near the contact interface.

All thermocouples had been calibrated against small range, mercury-in-glass thermometers of certified accuracy ± 0.02K, with the cold junctions in melting ice. Thermocouple outputs were indicated on a digital voltmeter capable of discrimination to 2.5 μV, corresponding to a temperature change of about 0.0625K.

Contact surface preparation

Two methods of surface preparation were used. The first was by lapping the contact faces together *in situ*, by alternating rotary motion, using fine carborundum paste. After lapping, the paste was cleaned off the contact surfaces without disturbing the assembly of the upper copper bar and tube. The surface roughness and hardness of the contact surfaces were obtained from two pieces of copper from the same bar as that used in the test rig and whose surfaces were lapped in an identical manner. The values were,

Surface roughness: 1.2–1.6 μm C.L.A.
Vickers hardness: 958–1000 N/m^2.

The second method was to lap the surfaces together and then coat them to a thickness of about 0.1 mm with silver-impregnated epoxy resin of the kind used to improve electrical contact. No hardener was added so that the coating remained in a plastic state, and would flow into the spaces surrounding local areas of contact, thereby reducing the thermal contact resistance.

Test procedure

Thermal tests began after the surfaces had been brought into contact and separated about a hundred times, isothermally, to ensure satisfactory mechanical operation.

The temperature distribution in each bar was observed after the contact surfaces had been meeting and parting cyclically for a sufficiently long time for a quasi-steady state to be reached. The length, l_T, of bar equivalent to the thermal resistance offered by the periodically contacting interface was obtained by extrapolation of the line of best fit among the temperature distribution points in each bar; the length, 2λ, of the bar equivalent to the thermal contact resistance of the interface was similarly determined with the contact surfaces permanently in contact.

The length, $2l_i$, of bar equivalent to the thermal resistance due to periodic interruption of the heat flow at the contact interface was then given by

$$2l_i = l_T - 2\lambda . \quad (2)$$

Serious errors in l_i can arise unless l_T and λ are known accurately.

Difficulties in obtaining l_i

When the surfaces were meeting and parting cyclically, the temperature distribution in each bar was subject to a slow variation when observed continuously over a long period of time. This was attributed to variation in the thermal contact resistance from cycle to cycle. Ancillary tests were conducted to try to shed some light on the matter.

Ancillary tests

Several successive determinations of thermal contact resistance were made. After each determination the contact surfaces were separated and then brought into contact again. Table 1 shows a typical sample of such observations.

Lapped contact surfaces

Table 1. Thermal contact resistance variation

Observation No.	Thermal contact resistance (K/W)
1	0.655
2	0.651
3	0.743
4	0.628
5	0.632
6	0.551
7	0.849

Static load on surfaces: 33.4N.
Height of fall: 2.54 mm.

The mean and standard deviation of the sample of thermal contact resistance data in Table 1 are 0.673 K/W and 0.096 K/W respectively. When corrected because the sample is small, the best estimate of standard deviation is 0.104 K/W. The distribution of thermal contact resistance within the sample is reasonably symmetrical and unimodal. Under these conditions, 95% of the distribution of the population lies within two standard deviations from the mean, [8]. Thus there is a probability of 0.95 that the thermal contact resistance will always lie between 0.465 K/W and 0.881 K/W.

Revised test procedure

Tests were conducted in the following order: (a) ancillary tests to determine successive values of thermal contact resistance; (b) tests to determine the thermal resistance offered by the periodically contacting surfaces; and (c) repetition of (a).

Because a truly quasi-steady state could not be achieved, the procedure for tests (b) was to observe temperatures 2 h after setting the frequency and proportion of the cycle time spent in contact, then to repeat the observation 5 min later to confirm that all temperatures were within ± 0.125K of their previous values. The procedure was repeated 30 min later.

Data processing

The length, $2l_i$, was determined from equation (2), but with 2λ replaced by the mean value, $2\lambda_m$, of the lengths of bar equivalent to the thermal contact resistance, arising from ancillary tests (a) and (c).

RESULTS

Comparison of experimental results with theoretical predictions

Figures 2 and 3 show values of (fl_i^2/α) obtained experimentally on the graphs obtained from the theoretical study, [7].

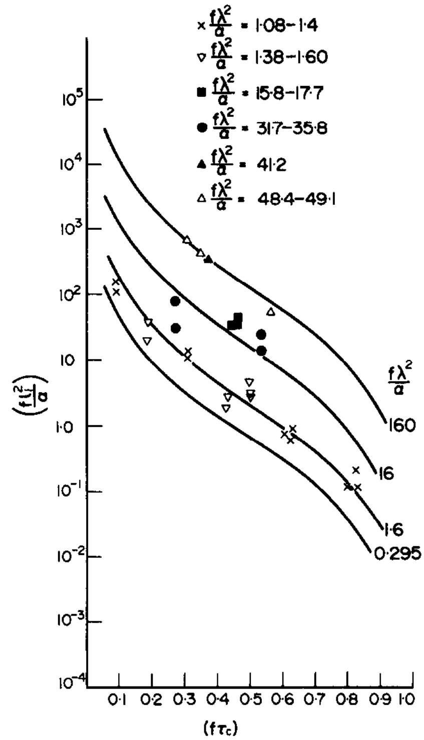

FIG. 2. Experimental and theoretical fl_i^2/α vs $f\tau_c$: lapped contact surfaces.

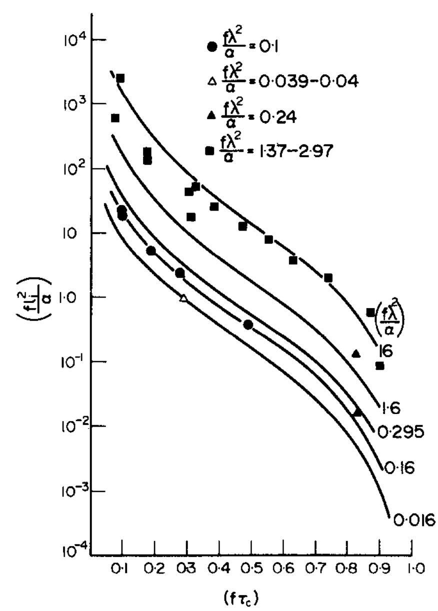

FIG. 3. Experimental and theoretical fl_i^2/α vs $f\tau_c$: silver impregnated epoxy resin coated surfaces.

With the lapped surfaces, Fig. 2, there was good agreement between the experimental and theoretical values of (fl_i^2/α) when $(f\lambda^2/\alpha)$ is 1.08 to 1.6. The value of $(f\lambda^2/\alpha)$ was then increased by increasing the frequency. (fl_i^2/α) at these higher $(f\lambda^2/\alpha)$ are mostly higher than theoretical although they vary with $(f\tau_c)$ in a similar manner. The contact surfaces which were coated with silver-impregnated epoxy resin behaved similarly.

The theoretical data, [7], was based on the assumption that, during the entire period of contact, the thermal resistance offered by the interface was constant and equal to the thermal contact resistance; i.e. the thermal resistance offered by the interface when the surfaces had been in contact for a long period of time. It is not possible to measure instantaneous values of thermal resistance offered by the interface to test this assumption, but it was thought that observation of the electrical resistance of the interface throughout each cycle might shed further light on the matter. This revealed an oscillation of the electrical resistance lasting about 12.5 ms when the surfaces came together. The effect of this transient was to increase the average electrical resistance during the period of contact to 0.26Ω compared with a steady state value of 0.21Ω. This result suggests that in equation (2) the value of 2λ used to compute l_i should be higher than the thermal contact resistance.

The steady state electrical resistance of the contact interface was 0.21Ω. Using Holm's expression $r = \rho/2a$ for the electrical resistance, r, of a single contact spot of radius, a, with material of resistivity, ρ, yields a contact area of radius 0.86×10^{-4} mm. This suggests that either (i) an electrically insulating film is present and the real contact is larger; or (ii) the above contact area is genuine and most of the heat flow through contact surfaces passes through the interstitial air gap or surface film.

The matter is unresolved by the data available.

Effect of impact

If the contact surfaces are brought together with impact instead of by gradual application of the load, the impulsive force on the surfaces will rise rapidly to a maximum and then oscillate with decreasing amplitude until the force on the surfaces is that due to the static load. The number of local contact areas would increase and the mean interstitial fluid gap would decrease with the force on the surfaces. If local welding occurs some welds may not break as the load relaxes, so that when equilibrium is attained, the contact area is greater and the interstitial fluid gap less than if the load were gradually applied. The thermal contact resistance would thus be reduced by impact loading of the surfaces.

Thermal contact resistance was observed at various values of impact. The impact was varied by altering the height through which the upper copper bar (Fig. 1) fell before the contact surfaces touched and also by altering the static load. Impact was quantified by calculating the momentum of the upper copper bar (and its attachments) just before contact.

Figure 4 shows the mean value and the limits of thermal contact resistance at various momenta for lapped contact surfaces and confirms that increasing the impact increases heat transfer significantly.

Surface wear

Table 2 shows a series of consecutive thermal contact resistance values. After each determination the surfaces were separated and closed once.

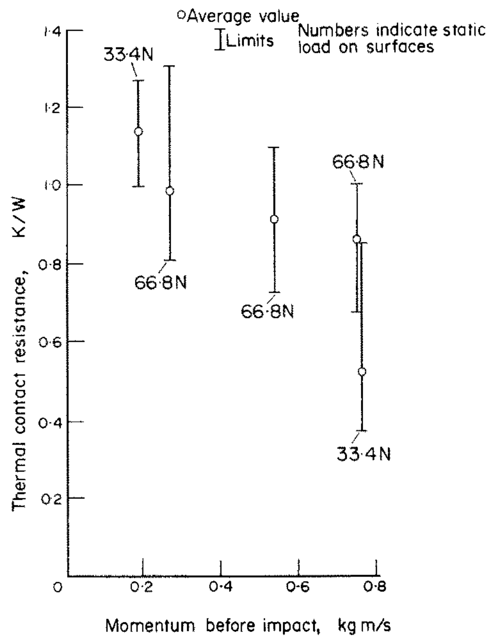

FIG. 4. Thermal contact resistance vs momentum before impact.

Table 2. Thermal contact resistance history

Observation No.	Thermal contact resistance (K/W)
*1	0.732
2	0.686
3	0.765
4	0.721
5	0.675
6	0.742
7	0.854
Periodic contact trials	
8	0.402
9	0.403
10	0.391
11	0.387
Periodic contact trials	
12	0.385
13	0.444
14	0.412
Periodic contact trials	
15	0.384
16	0.405
17	0.424
18	0.420
19	0.396
20	0.436

Static load = 33.4 N. Height of fall = 2.54 mm. Momentum before impact = 0.763 kg m/s.

* Freshly lapped surfaces.

The significant reduction in thermal contact resistance after the first set of periodic contact trials suggests that "bedding in" of the contact surfaces occurred.

However, after further periodic contact tests with higher impact, the impact was restored to very nearly the value obtaining for Table 2, but using a higher static load and a smaller height of fall. Successive values of thermal contact resistance shown in Table 3 are considerably larger than those shown in Table 1.

Table 3. Thermal contact resistance history

Observation No.	Thermal contact resistance (K/W)
21	0.868
Periodic contact trials	
22	0.793
23	0.838
24	0.981
25	0.841
Periodic contact trials	
26	1.030
27	0.975
28	0.745
29	0.686

Static load = 66.8 N.
Height of fall = 1.24 mm.
Momentum before impact = 0.755 kg m/s.

Visual examination of the contact surfaces revealed impact damage on a macro scale near the centre of the nominal contact area, together with a thin film of dirt or oxide. It seems likely that this altered the surface contact geometry increasing the interstitial air gap.

Accuracy of experimental results

Computation of the length, $2l_i$, using equation (2), is very sensitive to uncertainty in the values of l_T and 2λ. Errors in l_T and 2λ arise firstly due to transverse heat flows affecting the temperature at each thermocouple site [9]. If the temperature data points in each bar are scattered, a further uncertainty in lengths l_T and 2λ arises because of variation in fit of the straight line among the data points.

Analysis of a thermal resistance network approximate to the thermal circuit of test rig No. 2, showed that transverse heat flow caused the true value of thermal resistance offered by the contact interface to be about 11% greater than that indicated by experiments. The values of (fl_i^2/α) plotted on Figs. 2 and 3 are therefore too small by 21%.

Although scatter of the temperature data points in each bar seemed small, it was sufficient to cause a possible variation of $\pm 7\%$ in lengths l_T and 2λ when fitted to extreme positions among the points. For consistency, the temperature distribution lines were fitted by least squares technique.

However, to give an indication of the effect of a small uncertainty in l_T and 2λ on (fl_i^2/α), suppose both l_T and 2λ have the same uncertainty, ε, then

$$\text{Maximum}\left(\frac{fl_i^2}{\alpha}\right) = \frac{f}{4\alpha}\{l_T(1+\varepsilon)-2\lambda(1-\varepsilon)\}^2 \quad (3)$$

$$\text{Minimum}\left(\frac{fl_i^2}{\alpha}\right) = \frac{f}{4\alpha}\{l_T(1-\varepsilon)-2\lambda(1+\varepsilon)\}^2 \quad (4)$$

If, for example, $l_T = 2\lambda$, a condition met when $(f\tau_c) \simeq 0.5$, then

$$\frac{\text{maximum}\left(\frac{fl_i^2}{\alpha}\right)-\text{minimum}\left(\frac{fl_i^2}{\alpha}\right)}{\text{mean}\left(\frac{fl_i^2}{\alpha}\right)} = \frac{12\varepsilon}{1+9\varepsilon^2}. \quad (5)$$

The combined effect of the above sources of error on the values of (fl_i^2/α) plotted in Figs. 3 and 4 is that true values of (fl_i^2/α) could be $21\% \pm \{6\varepsilon/(1+9\varepsilon^2)\}$ greater than those plotted. Since the temperature distribution lines were fitted by least squares technique, the probable value of $\varepsilon \simeq 0.02$[10], leading to limits on (fl_i^2/α) being $+33\%$, $+9\%$.

CONCLUSIONS

The experimental work reported here demonstrated that a system where heat is transferred through periodically contacting surfaces behaves similarly to that predicted theoretically [7]. An approximation to the thermal resistance due to periodic interruption of heat flow at the contact interface can be made from the above theoretical data provided that the thermal contact resistance of the interface is known.

However, the thermal contact resistance offered by the contact interface has widely differing values each time the surfaces are brought into contact. The mean, standard deviation and probable (probability = 0.95) maximum and minimum values of thermal contact resistance encountered are shown in Table 4.

The variation in thermal contact resistance is probably due to changes in the interstitial fluid gap and the number, size and distribution of local contact areas, each time the surfaces come together.

After repeated contact and separation the copper contact surfaces suffered considerable damage on a macro scale and the average thermal contact resistance increased from 0.543 K/W to 0.862 K/W.

The experimental work on impact suggested that the thermal contact resistance could be halved by increasing the impact with which the surfaces came together fourfold. This in turn reduces the thermal resistance due to periodic interruption of the heat flow at the contact interface.

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Table 4. Mean, standard deviation and probable maxima and minima of thermal contact resistance (probability = 0.95)

Surface preparation	No. of observations	Mean thermal contact resistance (K/W)	Standard deviation (K/W)	Probable limits of thermal contact resistance (K/W) (min.)	(max.)
Lapped	13	0.632	0.0963	0.439	0.825
Lapped	20	0.523	0.1630	0.197	0.849
Damaged	9	0.862	0.1090	0.645	1.078
Contact with silver-impregnated epoxy resin	15	0.132	0.0484	0.035	0.229
Lapped and damaged surfaces above combined	42	0.630	0.1870	0.256	1.000

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ETUDE EXPERIMENTALE DU TRANSFERT DE CHALEUR ENTRE SURFACES EN CONTACT PERIODIQUE

Résumé—On décrit des expériences de transfert de chaleur par l'interface entre deux solides mis en contact et séparés périodiquement. Les résultats ont montré, qu'en dépit des grandes variations de la résistance thermique de contact entre les approches successives des deux surfaces, les travaux théoriques antérieurs pouvaient être utilisés pour prédire avec une précision raisonnable la résistance thermique moyenne dûe à l'interruption périodique du flux calorifique à l'interface.

On a également trouvé qu'une réduction importante de la résistance thermique pouvait être obtenue en augmentant la zone de contact entre les surfaces.

EXPERIMENTELLE UNTERSUCHUNG DES WÄRMEÜBERGANGS AN SICH PERIODISCH BERÜHRENDEN FLÄCHEN

Zusammenfassung—Es werden Untersuchungen für den Wärmeübergang beschrieben, bei dem sich die Flächen zweier fester Körper periodisch berühren. Die Ergebnisse zeigen, daß trotz großer Variationen der thermischen Kontaktzeiten frühere theoretische Arbeiten herangezogen werden können, um mit annehmbarer Genauigkeit den mittleren thermischen Widerstand zu berechnen, der sich infolge der periodischen Störung des Wärmestroms an der Kontaktfläche ergibt.

Es zeigte sich eine deutliche Verminderung des thermischen Kontaktwiderstandes, wenn der Anpreßdruck der Oberflächen erhöht wurde.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПЕРЕНОСА ТЕПЛА ЧЕРЕЗ ПЕРИОДИЧЕСКИ КОНТАКТИРУЮЩИЕ ПОВЕРХНОСТИ

Аннотация — Описываются эксперименты по исследованию переноса тепла через границу раздела между двумя периодически соприкасающимися твердыми телами. Результаты показали, что несмотря на большое изменение теплового сопротивления при переходе от одного момента контактирования к другому, для расчета среднего теплового сопротивления, возникающего при периодическом прерывании теплового потока на контактной границе, с достаточной точностью можно использовать результаты более ранних теоретических работ.

Было найдено, что значительное снижение теплового сопротивления можно найти, увеличив силу удара, с которым поверхности приходят в контакт.