Int. J. Heat Mass Transfer. Vol. 18, pp. 989–991. Pergamon Press 1975. Printed in Great Britain

SHORTER COMMUNICATIONS

THE EFFECT OF INTERFACE FLUID ON THERMAL CONTACT CONDUCTANCE

C. V. MADHUSUDANA*

(*Received* 15 *May* 1973 *and in revised form* 25 *November* 1974)

INTRODUCTION

THE HEAT transfer across a joint placed in a conducting medium can be considered to consist of the following modes: (i) conduction through the actual solid contact spots, and (ii) heat transfer through the gaps adjacent to the actual contact spots. This can be subdivided into:

(a) Conduction and convection through the fluid medium filling the voids. Of this, convection is negligible because the space between surfaces is microscopically small.
(b) Radiation—this mode is negligible up to a joint temperature of about 600°C [1].

The study of contact heat transfer has been the subject of many previous investigations but relatively few attempts, e.g. those of Laming [2] and Rapier *et al.* [3], have been made to isolate the solid spot and fluid conductances. Fenech and Rohsenow [1] tested all their joint combinations in one single environment, such as air, and, therefore, the relative importances of solid spot and fluid conductances could not be determined experimentally.

This article describes several heat-transfer experiments on contacts formed by different surface combinations in different environments with a view to assess the fluid conduction contribution to overall heat transfer. The values of corresponding solid spot conductances are also shown for comparison. Theoretical aspects are not discussed for want of space.

EXPERIMENTAL DETAILS

All of the heat-transfer tests to be discussed were conducted on a pair of 19 mm ($\frac{3}{4}$in) diameter cylindrical specimens assembled as a column to provide a plane joint. The experimental rig has been described elsewhere [4]. Table 1 gives a synopsis of the joint combinations and the environments used in the tests. It may be noted that, at any given temperature, the conductivity of air is one-and-a-half times, and that of helium five times, the conductivity of argon.

Table 1

No.	Specimens	Surface description	Environment	Mean interface temperature
(i)	Stainless steel Nilo 36 (an alloy very similar to Invar)	Crossed wedges 0·254 mm pitch	Vacuum and air	125°C
(ii)	Nilo 36 Uranium dioxide	Pyramids (0·635 mm pitch) Lapped flat and smooth (0·5 μm *CLA*)	Vacuum and air	100°C
(iii)	Zircaloy-2 Uranium dioxide	Rough flat surface (1·5 μm *CLA*) Rough flat surface (1·0 μm *CLA*)	Vacuum, argon and helium	185°C

* Lecturer in Mechanical Engineering, The University of N.S.W. (Broken Hill Division), Broken Hill, N.S.W. 2880, Australia.

The ridges on stainless steel and Nilo surfaces of the first pair can be approximately represented as shown in Fig. 1. The rough surfaces of the third pair were produced by blasting flat and smooth surfaces with micro glass beads. The deviation from flatness of all surfaces tested was less than $\frac{1}{2}$ μm except in the case of the first pair where the deviation was about 1·25 μm. The relevant properties of the materials tested are given in Table 2.

RESULTS AND DISCUSSION

All the results reported are from data collected during the first loading cycle only. At each contact pressure, the interface was tested for heat transfer both in vacuum and the fluid environments in consideration before proceeding to the next higher contact pressure.

The results of tests conducted in a conducting medium are subject to higher inaccuracies than those conducted in vacuum because of the following additional sources of error:

(i) By the very nature of tests, the heat loss to surroundings are considerably higher than those in vacuum. This is especially true if the medium is a good conductor like helium; in this case, the heat flux in top and bottom specimens agree typically to within 20 per cent compared to tests in vacuum where the agreement is always better than 8 per cent.

(ii) When determining the conductance of the fluid medium by subtracting the vacuum conductance from the total conductance measured in the gaseous environment we are assuming that the solid spot conductance remains invariant; this is not strictly true for the contact spot conductance in the presence of a medium is somewhat higher than that in vacuum. For example, when the ratio of actual contact area to nominal area of contacting surfaces is 1/100, the contact spot conductance increases by about 2·5 per cent when the vacuum surrounding the contact spot is replaced by a fluid with $c = 0{\cdot}01$ (c is the ratio of fluid to solid conductivity) and by about 14 per cent, when c is 0·10 [10]. In the present series of tests the maximum value of c used was about 0·02 (helium with Nilo/uranium dioxide combination).

Table 2

Material	Conductivity at 100°C (W/m deg C)		Effective flow pressure (hardness at 100 gm load)
			GPa
Stainless steel (type AISI 302)	16·3	[5]	3·92
Nilo 36	10·5	[6, 7]	2·45
Uranium dioxide	6·75	[8]	5·40
Zircaloy-2	14·0	[9]	1·96

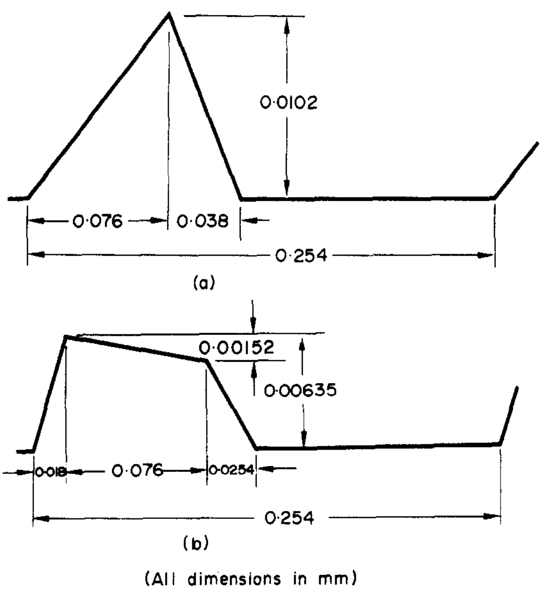

FIG. 1. Magnified views of ridges machined on (a) stainless steel surface (b) Nilo surface. Vertical magnification = 10 × horizontal magnification.

(iii) Tests of this kind take several days to complete as the medium has to be alternately introduced and removed; hence the effect of contact duration on conductance—conductance increases with time of application of load—could be significant [10].

Figures 2–4 show the results for stainless steel/Nilo, Nilo/uranium dioxide and zircaloy-2/uranium dioxide joints respectively. In each case both the solid spot and fluid conductances are shown plotted against contact pressure on a log–log basis.

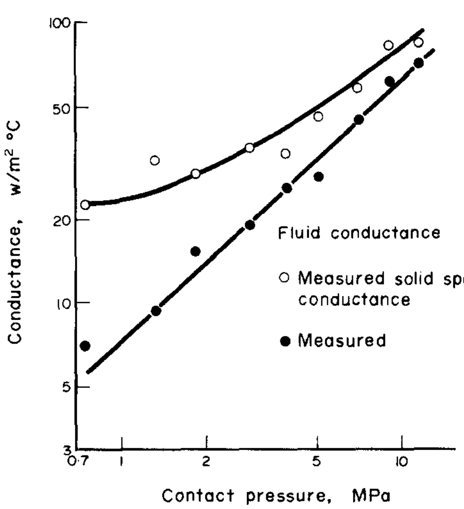

FIG. 2. Results for stainless steel/Nilo contact.

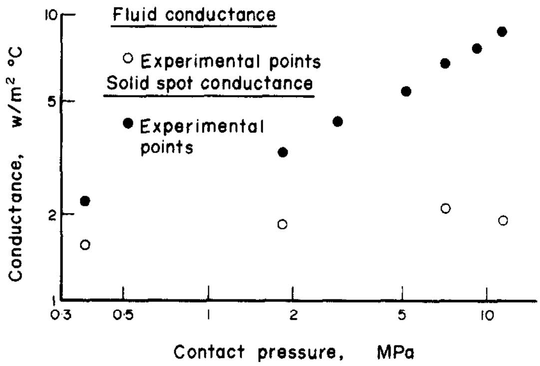

FIG. 3. Results for Nilo/uranium dioxide contact.

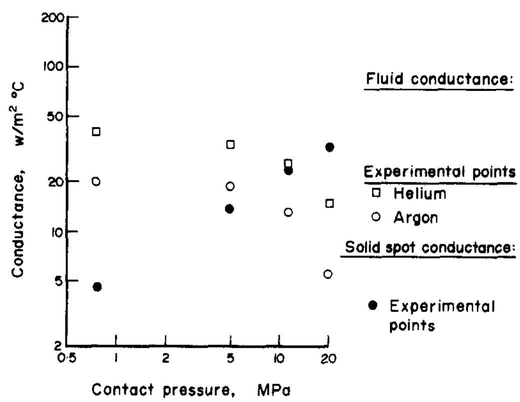

FIG. 4. Results for zircaloy-2/uranium dioxide contact.

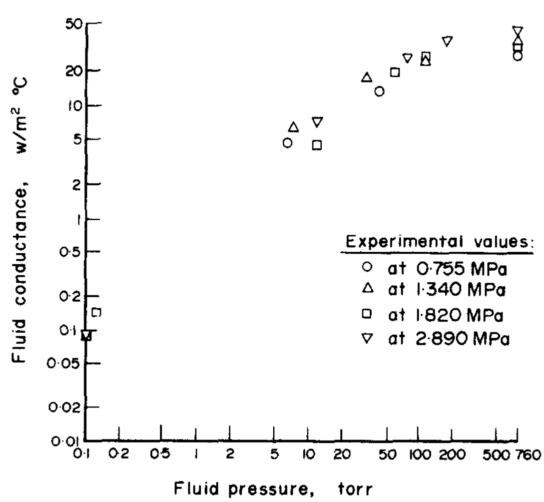

FIG. 5. Effect of fluid pressure variation on fluid conductance (stainless steel/Nilo contact in air).

In all cases it can be seen that the increase in conductance due to the presence of the fluid medium is considerable at low contact pressures but the contact spot conductance predominates at higher pressure. This is in agreement with the results of Sanderson [11]. The apparent decrease in gaseous conduction contribution to contact heat transfer as the contact pressure is increased is an anomaly which has also been noted by Ross and Stoute [12] in some of whose tests the fluid conductance was even negative! These results emphasize the difficulties in obtaining accurate information from tests of this kind for reasons mentioned earlier. Also, at high contact pressures both the solid spot conductance and the total conductance are large and the relatively small fluid conductance is determined as a difference between two large quantities. This is likely to be inaccurate.

Figure 5 shows the variation in fluid (air) conductance with fluid pressure for the stainless steel/Nilo combination at four different contact pressures. However, over the small contact pressure range considered (0·755–2·89 MPa), the variation in fluid conductance is small at any given fluid pressure—a fact confirmed by Fig. 2. The results show that the decrease in fluid conductance as the gas pressure is reduced is particularly significant at gas pressures below 100 torr, i.e. when the mean free path for air is greater than about ten times the mean physical gap. Boeschoten and Van der Held [13] observed similar trends.

CONCLUSIONS

(i) The contact conductance improves in the presence of a conducting medium. For all fluids such improvement is significant at low contact pressures; the solid spot conductance predominates at high pressures. When the interface medium is a good conductor such as helium, the improvement is significant over the entire contact pressure range of the tests.

(ii) The results for contacts formed by flat surfaces show agreement with those of previous workers.

(iii) The fluid conduction contribution to heat transfer across a joint at any contact pressure decreases as the fluid pressure is reduced. Such reduction seems to be significant at absolute pressures below 100 torr.

Acknowledgements—The author's grateful thanks are hereby offered to Monash University where the present work was done during his tenure as a research scholar and to Professor A. Williams for many helpful suggestions and comments.

REFERENCES

1. H. French and W. M. Rohsenow, Thermal conductance of metallic surfaces in contace, USAEC Report NYO-2136, M.I.T. Cambridge, Mass. (1959).
2. L. C. Laming, Thermal conductance of machined metal contact, in *Proceedings of International Developments in Heat Transfer*, pp. 65–76. A.S.M.E., New York (1961).
3. A. C. Rapier, T. M. Jones and J. E. McIntosh, The thermal conductance of uranium dioxide/stainless steel interface, *Int. J. Heat Mass Transfer* **6**, 397–416 (1963).
4. A. Williams, Heat transfer through metal to metal joints, in *Proceedings of the Third International Heat Transfer Conference, Chicago*, Vol. IV, pp. 109–117. A.I.Ch.E., New York (1966).
5. *Mechanical and Physical Properties of the Austenitic Chromium–Nickel Stainless Steels at Elevated Temperatures*, p. 23. International Nickel, London (1966).
6. *The Nilo Series of Controlled Expansion Alloys*, p. 4. Henry Wiggin, London (1965).
7. J. W. Sands, *Invar, Elinvar and Related Iron–Nickel Alloys, Metals and Alloys*, Vol. 3, 159–165 (1932).
8. W. W. Plotnikoff and G. A. Tingate, Australian Atomic Energy Commission Research Establishment, Private Communication (1970).
9. B. J. Seddon, Zirconium Data Manual, TRG Report 108(R), U.K.A.E.A. (1962).
10. C. V. Madhusudana, Heat flow across plane and cylindrical joints, Ph.D. Thesis, Monash University, Clayton, Victoria, Australia (1972).
11. P. D. Sanderson, Heat transfer from uranium fuel to the Magnox Can in a gas cooled reactor, in *Proceedings of International Developments in Heat Transfer*, pp. 53–64. A.S.M.E., New York (1961).
12. A. M. Ross and R. L. Stoute, Heat transfer coefficient between UO_2 and Zircaloy-2, Report No. CRFD-1075, Atomic Energy of Canada Limited, Ontario (1962).
13. F. Boeschoten and E. F. M. Van der Held, Thermal conductance of contacts between aluminium and other metals, *Physica, s'Grav.* **23**, 37–44 (1957).

Int. J. Heat Mass Transfer. Vol. 18, pp. 991–993. Pergamon Press 1975. Printed in Great Britain

NOTE ON A PAPER BY KIERKUS

N. RILEY
University of East Anglia, Norwich, England

(*Received* 28 *March* 1974 *and in revised form* 25 *September* 1974)

NOMENCLATURE

g,	acceleration due to gravity;
Gr,	Grashof number $g\beta L^3\nu^{-2}(T_w - T_\infty)\cos\phi$;
L,	reference length;
p,	pressure;
T,	temperature;
T_w,	wall temperature;
T_∞,	temperature of ambient fluid;
x, y,	Cartesian co-ordinates.

Greek symbols

β,	coefficient of expansion;
θ,	dimensionless temperature $(T - T_\infty)/(T_w - T_\infty)$;
κ,	thermal conductivity;
ν,	kinematic viscosity;
ρ,	density;
σ,	Prandtl number ν/κ;
ϕ,	angle of plate to vertical;
ψ,	stream function.

INTRODUCTION

IN THIS note we re-consider, briefly, the problem of the flow induced when a semi-infinite flat plate, heated to a uniform temperature in excess of the ambient temperature, is inclined at an angle ϕ to the vertical. The Grashof number Gr, defined below, is assumed to be large. The problem has previously attracted the attention of Kierkus [1]. The main feature of the flow when compared with the case $\phi = 0$ is the asymmetry, above and below the plate, due to the normal component of the gravitational field g. The method of solution is to expand the flow quantities in powers of $Gr^{-\frac{1}{4}}$. The structure of the primary boundary layer is identical with