EXPERIMENTAL INVESTIGATION ON THE OVERALL THERMAL RESISTANCE OF SPHERE-FLAT CONTACTS

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Abstract

This paper describes the equipment, procedure, and results of an experimental investigation on the overall thermal resistance of sphere-flat contacts. Two spherical specimens having diameters of 1 and 2 in. in elastic contact with relatively smooth flats were examined. Tests were conducted with air and argon, pressures ranging from atmospheric conditions to 10^{-5} mm Hg. The effect of a lubricant, with and without air present, also was studied. Mechanical loads were varied from 3.6 to 160 lb, thereby producing contact radii varying from 4.34×10^{-3} to 1.53×10^{-2} in. The experimental results are in good agreement with the theory previously published by these authors.

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Nomenclature

A = sample cross-sectional area
a = contact radius
D = diameter of contacting spherical solids
k = thermal conductivity, Btu/hr-ft-°F
R = thermal resistance, °F/Btu/hr
ΔT_e = extrapolated temperature difference, °F
L = dimensionless loading parameter (D/2a)
P_g = gas pressure, mm Hg

Introduction

Sphere-flat contacts have a relatively simple geometry, which is amenable to mathematical analysis. It is believed that a full understanding of the various modes of heat transfer across these relatively simple contacts will permit one to analyze the more complex problem of heat transfer across the sphere-race contact,[1,2] found in instrument bearings.

A paper has been published[3] which deals with the theoretical aspect of this problem. The theory, based upon decoupled and coupled models, predicts the overall resistance of a sphere-flat contact under 1) vacuum conditions including radiative effects, 2) continuum conditions, and 3) the more complex situations of slip and transition regimes. The theory also predicts the effect of a lubricant with and without a gas present. The theory is based upon elastic contact between smooth solids and is limited to the first loading cycle only.

The objective of the experimental program described in this paper was to measure the overall resistance of sphere-flat contacts and to compare the test results obtained for various conditions with predicted values. The paper presents a considerable amount of test data not available in the literature.

Experimental Equipment, Test Specimens, and Test Procedure

Equipment

The test program was carried out in a modified vacuum system consisting of a base plate, bell jar, and a mechanical and diffusion pump. With this system, tests could be con-

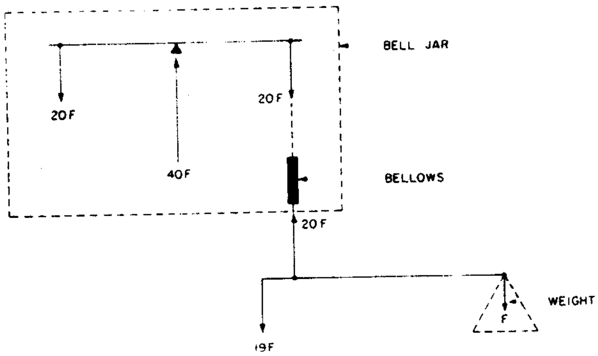

Fig. 1 Schematic of loading system.

ducted with air and argon pressures ranging from atmospheric conditions down to 10^{-5} mm Hg. Pressure measurements were obtained by means of a manometer for pressures ranging from 740 to 10 mm Hg, by means of a McLeod gage for pressures ranging from 5 to 10^{-2} mm Hg, and by means of an ionization gage for pressures below 10^{-2} mm Hg.

Axial loads were applied directly to the test specimens by means of dead weights for light loading, as well as by means of an external mechanical loading device (Fig. 1). The contact load was determined by means of a calibrated load cell located a substantial distance from the heater so that it would not be influenced by temperature effects.

A cartridge heater supplied the desired heat flow rate across the sphere-flat contact. An input of 35 w was used to establish sufficiently large temperature drops across the contact and between successive thermocouples. The heat was removed from the system through a water-cooled heat sink located at the base of the system. The entire test assembly was insulated by ½-in.-thick urethane insulation and encased in

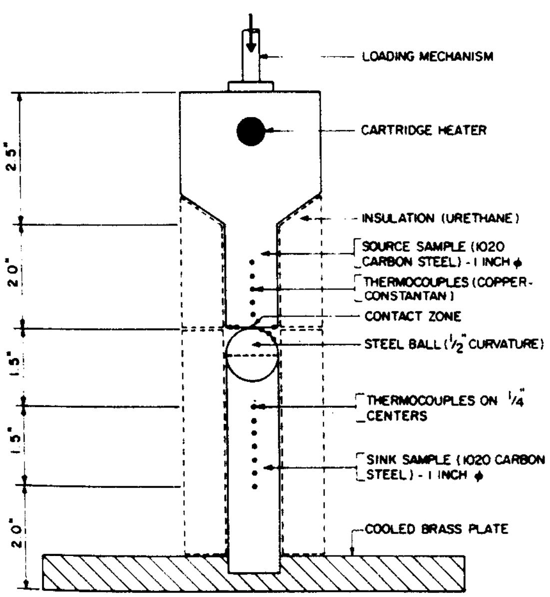

Fig. 2 Diagram of 1-in. ball-flat contact.

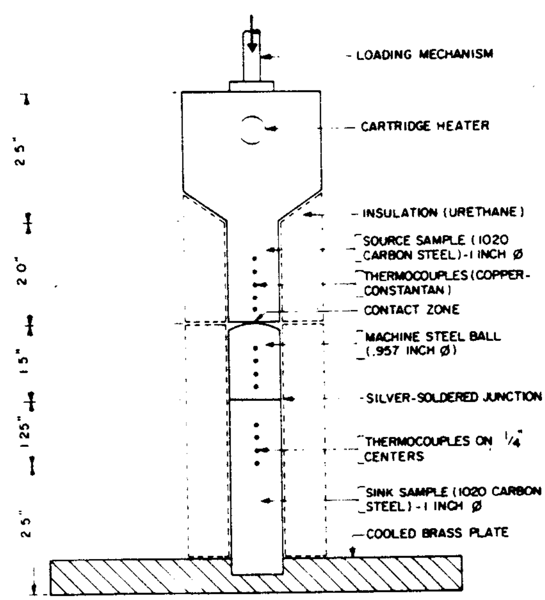

Fig. 3 Diagram of machined 2-in. ball-flat contact.

aluminum foil to minimize heat losses by radiation and convection to the surroundings. The two heat specimens as assembled for testing are shown schematically in Figs. 2 and 3.

Copper-constantan thermocouples were used to measure the temperature. They were firmly attached to the test specimens, as shown in Fig. 4. All thermocouples were soft-soldered into 0.02-in.-diam holes 0.10 in. deep. The holes were spaced 0.25 ± 0.002 in. apart starting 0.50 in. from the interface.

For the 1-in.-diam tests, five thermocouples were located in the source specimen (flat), and seven thermocouples were located in the sink specimen (sphere). Three additional thermocouples were located in the flat near the contact area, and three thermocouples were located on the spherical surface. These were positioned 0.25, 0.30, and 0.40 in. from the center of the origin of the contact area. These thermocouples were used to verify the extrapolation technique for determining interface temperatures.

For the 2-in.-diam tests, five thermocouples were located in the source specimen, and eight thermocouples were located in the sink specimen, which consisted of two sections. In one section, machined from a 2-in. ball, four thermocouples were located and used in the determination of the interface temperature. In the lower section, four thermocouples were used to determine the heat flow rate across the sphere-flat contact.

Test Specimens

The test specimens were fabricated from 1020 carbon steel rods of 1-in. diam and two carbon steel balls having diameters of 1 and 2 in., respectively. The source specimen was

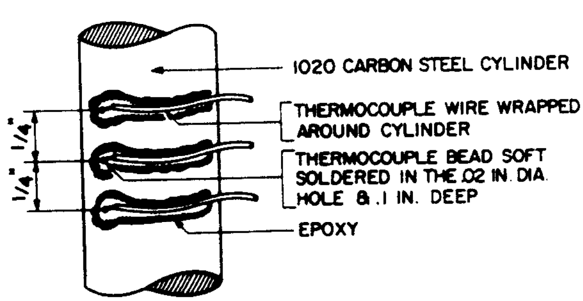

Fig. 4 Thermocouple attachment.

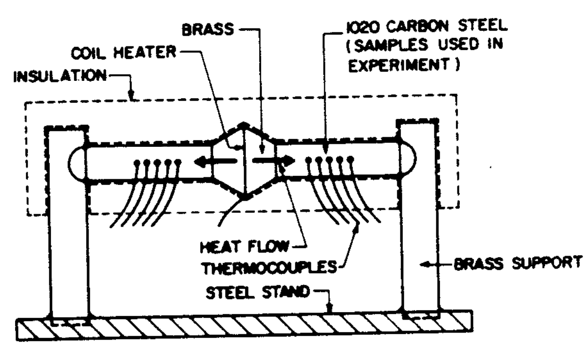

Fig. 5 Thermal conductivity test apparatus.

first machined to the dimensions shown in Figs. 2 and 3. The flat surface was first surface-ground, then polished with fine sandpaper to produce surface roughnesses of 30 and 5 µin. (rms). The surface roughness of the flats was determined by means of a Talysurf.

The two sink specimens were prepared in the following manner. The 1-in. ball was silver-soldered into a hemispherical cavity machined at one end of a 1020 carbon steel rod. The surface of the ball was buffed to remove any oxides that may have formed during the soldering.

The 2-in. ball was machined to the dimensions shown in Fig. 3 and silver-soldered to the flat end of a 1020 carbon steel rod. The spherical surface was buffed to remove oxides.

The physical and thermal properties of the test specimens are reported in Table 1. The thermal conductivity of the 1020 carbon steel rods used in the tests was determined experimentally by means of the simple test device shown schematically in Fig. 5. The well-insulated system was placed in a vacuum, where the tests were conducted.

Test Fluids

The fluids used in the tests were air, argon, and vacuum oil. The thermal properties of these fluids are reported in Table 2. The mean free paths of air and argon were taken to be 2.52×10^{-6} and 2.62×10^{-6} in., respectively, at a temperature of 59°F and 760 mm Hg. The reported accommodation co-

Table 1 Physical and thermal properties of test specimens

Specimen	Properties					
	Poisson's ratio	Modulus of elasticity, psi	Thermal conductivity, Btu/hr-°F-ft	Hardness (Rockwell)	Surface roughness, µin.	Emissivity
Flat (1020 carbon steel)						
Sample #1	0.3	30×10^6	30.5[a]	26	30	0.9[b]
Sample #2	0.3	30×10^6	30.5	26	5	0.8
Sphere (carbon steel)						
1-in.diam	0.3	30×10^6	29[c]	35	...	0.2
2-in.diam	0.3	30×10^6	23.5	35	...	...

[a]Stelco of Canada Co. Ltd. quoted 30 ± 10% Btu/hr-°F-ft (thermal conductivity from test).

[b]Ref. 5.

[c]S.K.F. Bearing Co. Ltd. quoted 25 ± 10% Btu/hr-°F-ft (thermal conductivity from test).

Table 2 Thermal properties of gases and oil

Fluid	Temperature	Properties		
		Thermal conductivity, Btu/hr-°F-ft	Accommodation coefficient	
			Sphere	Flat
Air	60°F	0.015 [a]	0.87	0.92 [b]
	100°F	0.016	...	...
	160°F	0.017	...	...
Argon	290°K	0.010 [c]	0.90	0.90
	300°K	0.0103	...	...
	310°K	0.0105	...	...
	320°K	0.0108	...	...
	330°K	0.0111	...	...
	340°K	0.0116	...	...
Oil	50°F	0.0780 [d]	...	...
	75°F	0.0774	...	...
	100°F	0.0768	...	...
	125°F	0.0762	...	...
	150°F	0.0756	...	...
	175°F	0.0750	...	...
	200°F	0.0744	...	...

[a] Ref. 5.

[b] Ref. 6.

[c] Ref. 7.

[d] Cities Service Oil Co.

efficients are assumed to be reasonably good average values for the combination of gases and solids used in the tests.

Test Procedure

All tests were conducted in the following manner. The mechanical load was set, and heat supplied to the test specimen. Approximately 12-24 hr were required for steady-state conditions to prevail. A strip chart recorder monitored a thermocouple location near the contact, and when there was no change in the temperature reading (taken over approximately 3 hr) it was judged that steady-state conditions prevailed. The thermocouple readings were then recorded, and the overall resistance was determined by means of a computer program. The temperature gradient and difference were determined by the least-squares method.

The load was increased in increments and test data obtained for each load. These preliminary tests were conducted to ascertain whether the equipment functioned properly, whether the surface characteristics of the flat were smooth enough, and whether the computer program was functioning properly.

Having shown that the system was functioning properly, subsequent tests were conducted as follows. For a fixed load, the system would be filled with a fluid such as air, and thermocouple readings would be monitored and recorded when steady-state conditions were observed (same as previous). For a small change in pressure of the system, steady-state conditions prevailed after approximately 3 hr. For a large change in pressure of the system, steady-state conditions prevailed after 24 hr. Air tests were conducted at numerous pressures ranging from atmospheric conditions down to 10^{-5} mm Hg. Tests also were conducted with gas pressures increasing from 10^{-5} mm Hg to atmospheric conditions. The mechanical load then was increased, and air tests were repeated at different gas pressures. Air tests were conducted at every load, whereas argon test data were obtained only at several loads. Argon test data were obtained at numerous gas pressures varying from atmospheric down to 10^{-5}mm Hg. The effect of oil was observed under vacuum conditions as well as with air present under various gas pressures.

At the conclusion of a loading cycle, the sphere specimen was replaced with a new undeformed specimen, and the flat specimen was machined and repolished to remove any permanent deformation. Before each test, the surface roughness was measured and recorded.

Thermal Resistance and Data Reduction

The overall thermal resistance is defined as the total temperature drop across the sphere-flat contact divided by the total heat flow rate across the contact:

$$R = \Delta T_e / Q \qquad (1)$$

In Eq. (1), ΔT_e is the extrapolated temperature difference at the contact. It is determined by a linear extrapolation of steady-state thermocouple readings observed in undisturbed regions located on either side of the contact (Figs. 6 and 7).

The total flow rate was calculated by means of Fournier's equation

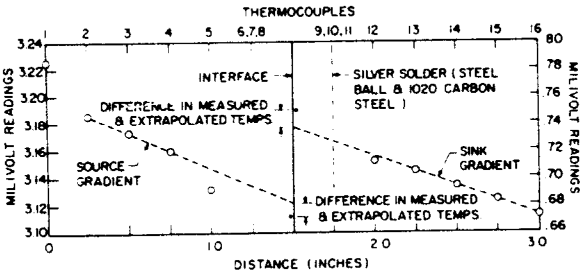

Fig. 6 Evaluation of temperature and gradient in 1-in. tests.

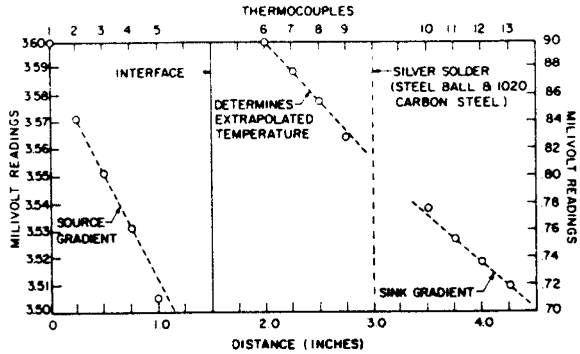

Fig. 7 Evaluation of temperature and gradient in 2-in. tests.

$$Q = k\,A(\Delta T/\Delta x) \qquad (2)$$

where k and A are the thermal conductivity and the heat flow area of the sink specimen (1020 carbon steel), and $\Delta T/\Delta x$ is the temperature gradient measured in the sink specimen (Figs. 6 and 7).

A computer program was used to determine the extrapolated temperatures of the sphere-flat contacts, the extrapolated temperature difference, and the temperature gradients within the source and sink specimens.

Test Results and Discussion

Vacuum Tests

The results of the vacuum tests for the 1-in.-diam sphere-flat contact are reported in Tables 3-5 and Figs. 8 and 9. All tests were conducted at a pressure of 10^{-5} mm Hg. The mean interface temperature ranged from about 150° to 80°F, de-

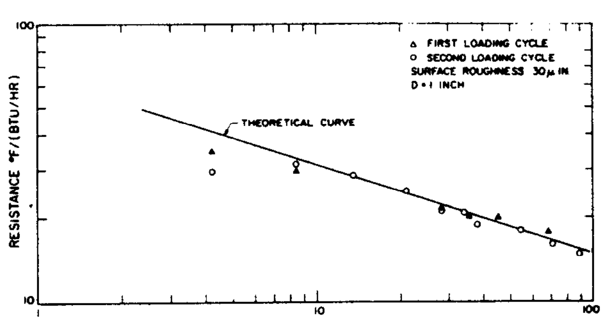

Fig. 8 Thermal resistance vs load for vacuum conditions (roughness 30 μin.).

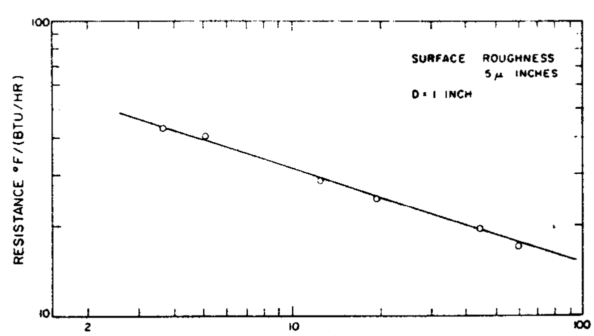

Fig. 9 Thermal resistance vs load for vacuum conditions (roughness 5 μin.).

Table 3 Difference between extrapolated and measured temperature

Experimental			Extrapolated			
Sink temp.	Source temp.	Temp. diff.	Sink temp.	Source temp.	Temp. diff.	Temp. diff,%[a]
63.35	107.97	44.62	62.23	108.08	44.85	-0.51
62.85	110.96	48.11	62.85	110.94	48.09	0.04
63.15	109.97	46.82	63.17	109.79	46.62	0.42
63.12	108.93	45.81	63.17	108.91	45.74	0.16
63.24	108.19	44.95	63.45	108.14	44.69	0.59
63.26	101.86	38.60	63.23	101.93	38.69	-0.23
63.27	107.00	43.73	63.41	107.05	43.64	0.20
62.77	105.23	42.46	63.05	104.84	41.79	1.58
64.06	102.55	38.49	63.90	102.52	38.62	-0.33
64.39	101.35	36.96	64.32	101.24	36.92	0.08
64.39	101.44	37.05	64.32	101.44	37.12	-0.18
63.68	100.29	36.61	63.37	100.38	37.01	-1.09
63.94	99.86	35.92	63.38	99.92	36.24	-0.90
64.07	98.38	34.31	63.96	98.42	34.46	-0.45
64.07	98.80	34.73	63.86	98.79	34.92	-0.56
65.45	169.05	103.63	65.35	168.85	103.5	0.12
66.11	165.33	99.23	65.72	165.09	99.37	-0.15
67.27	166.23	99.01	67.23	166.08	98.85	0.16
67.56	162.97	95.41	67.73	162.68	94.95	0.48
69.34	166.95	97.61	68.68	166.67	97.99	-0.39
69.42	164.69	95.27	68.84	164.46	95.62	-0.37
66.98	165.32	98.34	66.77	164.97	98.2	0.13
68.48	161.80	93.32	68.13	161.60	93.47	-0.16
69.47	158.75	89.28	69.06	158.58	89.51	-0.27
69.28	154.99	85.72	68.95	154.81	85.96	-0.16
70.04	152.85	82.82	69.6	152.59	82.98	-0.20
70.57	149.49	78.93	69.75	149.51	79.96	-1.06

[a]The mean for the total data is -0.305%, and the standard deviation is 0.528%.

pending upon the mechanical load and the heat input to the test specimens. The temperature drop across the sphere-flat contact ranged from about 30° to 160°F. Since the subsequent test specimens did not have thermocouples adjacent to the contact, the temperatures at the contact were determined by extrapolating temperature readings from the undisturbed regions located on either side of the contact to the interface. Table 3 shows that the technique of extrapolating the temperature readings is in excellent agreement with the measured readings. The percent difference did not exceed 1.58%, and the mean difference for all test results was -0.304%. These data correspond to several different loads.

Table 4 and Fig. 8 correspond to the tests conducted with the 1-in.-diam sphere in contact with a flat having a surface roughness of 30 μin. (rms). Both first and second loading cycle test data are reported. It can be seen very clearly

Table 4 Thermal resistance for vacuum conditions (roughness 30 μin.)

Load, lb	L	Measured resistance, °F/Btu/hr	Theoretical resistance, °F/Btu/hr
4.2 [a]	109.4	34.7	42.0
8.4	86.8	30.0	33.6
13.4	74.3	25.9	29.0
20.8	64.3	25.2	25.2
28.0	58.1	21.6	22.9
35.3	53.8	20.4	21.2
44.5	49.8	20.4	19.6
68.0	43.2	18.0	17.1
4.2 [b]	109.4	29.6	41.6
8.6	86.1	30.7	33.2
13.4	74.3	28.7	28.8
21.0	64.0	25.1	24.9
28.0	58.1	21.5	22.7
34.0	54.5	21.0	21.3
39.0	52.0	19.0	20.4
55.0	46.4	18.2	18.3
71.0	42.6	16.3	16.8
89.0	39.5	15.0	15.6
109.0	36.9	14.2	14.6
124.0	35.4	13.5	14.0
144.0	33.7	12.6	13.4

[a]First loading cycle.
[b]Second loading cycle.

Table 5 Thermal resistance for vacuum conditions (roughness 5 μin.)

Load, lb	L	Measured resistance, °F/Btu/hr	Theoretical resistance, °F/Btu/hr
3.6	115	43.2	43.3
5.0	103	40.1	39.1
12.5	76	28.6	29.3
19.6	65.4	25.0	25.4
44.0	50	19.7	19.6
60.0	45.1	17.2	17.7
105.0	37.4	14.3	14.8

that the agreement between these tests and theory[3,4] based upon smooth surfaces is not good at loads less than about 10 lb or L equal to or greater than about 80. The dimensionless parameter[3,4] L is a measure of the relative size of the contact. For a fixed system, L varies inversely as the load to the 1/3 power. For loads greater than 10 lb, there is excellent agreement between test and theory, and therefore the effect of surface roughness is negligible.

The plastic deformation of the sphere and, in particular, the surface asperities of the flat result in the lower resistance test data observed at the lightest loads during the second loading cycle, as seen in Fig. 8. The agreement between the test results and theoretical values is excellent over the entire load range when the flat is polished to a surface roughness of 5 μin. (rms), as can be seen in Table 5 and Fig. 9.

The vacuum test results for the 2-in. spherical solid-flat contact are reported in Table 6. For these tests, the flat was polished to produce surface roughnesses comparable to those in the 1-in.-diam tests. It is seen that the agreement between experiment and theory is excellent when radiation is included.

Air Tests

The air test results are reported in Table 6 for several loads and numerous air pressures ranging from 10^{-5} to 740 mm Hg. Figure 10 shows test results at the minimum load of 3.6 lb and a maximum load of 105 lb. All test data correspond to the first loading cycle only. It can be seen that the overall resistance was 42.8°F/Btu-hr, corresponding to the lightest load under vacuum conditions. The minimum overall resistance was observed to be 11.0°F (Btu-hr), corresponding to the largest load under continuum conditions. Figure 10 demonstrates clearly that, for light loading, the effect of air is very important and the air resistance is comparable to the constriction resistance for gas pressures in excess of 10 mm Hg. On the other hand, at the largest loading the heat flow through the contact is dominant, and the effect of air is less important even when the gas pressure is 740 mm Hg. In Fig. 10, one can see the three distinct gas regimes: continuum, slip, and rarefied. These regimes are important for the very light loads when gas effects are to be considered for pressures ranging from 10^{-1} to 740 mm Hg.

It should be noted that the test data designated by A and B in Fig. 10 correspond to the same gas pressure. Test data A were obtained by proceeding from vacuum tests to higher-pressure tests, whereas test data B were obtained by proceeding from continuum conditions. These measured values are repeatable. Thus it is possible to observe two resistances corresponding to a particular gas pressure. This effect was observed only in the 10^{-2} to 10^{-1} mm Hg. range.

The agreement between experiment and theory is excellent over the entire pressure range for all loads, as shown in Table 6. The theory[3,4] was based upon the decoupled model and includes the effect of radiation across the gas gap. For gas pressures below 100 mm Hg, the slip regime analysis was used for predicting the overall resistance. In the theory, it was

Table 6 Thermal resistance for air tests

Load, lb	L	Pressure, mm Hg	Measured resistance, °F/Btu/hr	Theoretical resistance, °F/Btu/hr
3.6[a]	115	10^{-5}	42.8	43.3
		0.05	42.8	43.3
		0.100	33.5	43.4
		0.125	43.3[b]	43.3
		0.135	33.1	34.2
		0.200	32.4	32.9
		0.25	31.2	32.1
		0.475	30.0	30.0
		0.60	29.5	29.6
		1.8	26.5	26.1
		4.4	23.8	23.9
		10.0	21.1	22.4
		40.0	21.1	19.8
		100.0	20.0	19.4
		400.0	18.9	19.1
		600.0	19.0	19.1
		740.0	19.2	19.5
5.0	103.2	10^{-5}	37.5	39.1
		0.05	38.6	39.2
		0.16	30.1	31.5
		0.35	27.4	29.2
		0.65	26.3	27.5
		1.1	25.5	26.2
		2.0	23.8	24.8
		20.0	20.5	21.5
		100.0	19.2	19.0
		200.0	19.1	19.0
		490.0	18.9	18.7
		740.0	18.2	18.7
12.5	76.0	0.05	28.6	29.3
		0.9	22.9	21.8
		1.4	20.5	21.1
		10.0	17.6	19.1
		50.0	17.9	17.7
		200.0	16.7	16.9
		500.0	16.6	16.9
		740.0	16.5	16.9
44.0	50.0	10^{-5}	19.7	19.6
		0.05	19.7	19.6
		0.275	16.9	17.0
		0.700	16.5	16.2
		4.3	15.7	15.1
		20.0	14.9	14.8
		70.0	14.5	14.5
		400.0	13.9	13.9
		740.0	13.9	13.9

(continued on next page)

Table 6 (continued)

Load, lb	L	Pressure, mm Hg	Measured resistance, °F/Btu/hr	Theoretical resistance, °F/Btu/hr
60.0	45.0	10^{-5}	17.2	17.7
		0.05	17.8	17.7
		0.45	15.2	15.3
		1.1	14.4	14.7
		3.3	14.1	14.2
		20.0	13.8	13.8
		100.0	13.1	13.0
		400.0	13.2	13.0
		740.0	13.1	13.1
105.0	37.4	10^{-5}	14.3	14.8
		0.5	14.6	14.8
		0.6	12.5	12.9
		1.75	12.2	12.5
		20.0	11.8	12.1
		100.0	11.5	11.4
		400.0	10.9	11.6
		740.0	11.0	11.6
3.8 [c]	179.5	10^{-5}	36.9	37.2
		0.8	24.4	23.5
		2.3	20.2	18.7
		20.0	16.7	15.1
		100.0	15.1	12.3
		400.0	15.4	12.3
		740.0	13.9	12.0
30.5	89.6	10^{-5}	18.8	19.4
		0.05	18.6	19.4
		0.625	15.2	14.8
		2.8	13.3	13.0
		20.0	11.6	11.9
		100.0	10.9	10.6
		740.0	11.3	10.7

[a]Testing on 1-in.-diam ball (3.6-105 lb).

[b]Testing from hard vacuum to continuum.

[c]Testing on 2-in, ball (3.8 and 30.5 lb).

assumed that the effective lower limit for the slip regime was 5 contact radii.[3,4]

Argon Tests

The argon test results for the 1-in.-diam sphere-flat contact are reported in Table 7 and in Figs. 11 and 12. Tests were obtained at four different loads at numerous gas pressures ranging from about 0.05 to 740 mm Hg. It can be seen under continuum conditions the overall resistance goes from 23.3°F/Btu-hr at the lightest load

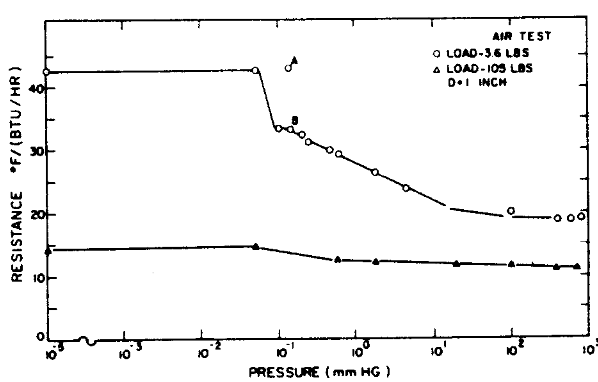

Fig. 10 Thermal resistance vs pressure at constant load.

Table 7 Thermal resistance for argon tests

Load, lb	L	Pressure, mm Hg	Measured resistance, °F/Btu/hr	Theoretical resistance, °F/Btu/hr
3.6	115	0.55	27.2	33.1
		0.75	27.6	32.3
		1.1	27.9	31.3
		2.0	27.8	29.8
		2.1	26.7	29.7
		4.6	26.5	27.9
		4.9	27.4	27.8
		10.0	25.3	26.4
		80.0	23.7	22.8
		100.0	23.4	23.5
		200.0	22.6	23.5
		400.0	23.5	23.5
		600.0	22.3	23.6
		740.0	23.3	23.6
12.5	76.0	0.05	30.1	29.3
		0.18	26.4	25.9
		0.7	24.0	24.0
		2.4	23.1	22.5
		20.0	20.9	21.1
		100.0	19.8	19.7
		400.0	19.6	19.8
		740.0	19.5	19.8
44.0	50.0	0.15	18.2	18.1
		0.4	17.5	17.5
		1.2	17.2	16.8
		20.0	15.9	16.0
		100.0	15.9	15.4
		400.0	15.8	15.4
		740.0	15.8	15.4
105.0	37.4	0.6	13.1	13.4
		3.0	12.6	13.0
		20.0	12.2	12.9
		110.0	12.0	12.5
		450.0	12.1	12.5
		740.0	12.0	12.5

(L = 105) to 12.0°F/Btu-hr at the largest load (L = 36). The agreement between experiment and theory based upon the decoupled model[3,4] is excellent over the entire load range. The largest discrepancy between experiment and theory is observed at the lightest load, when the pressure in the system was observed to be 0.05 to 0.10 mm Hg. It is believed that this difference is due to the presence of air, which leaks into the system at these reduced pressures. The difference between test and theory at low gas pressures decreases with increasing load because the heat-flow rate through the contact becomes the dominant mode of heat transfer.

Lubricant Tests

The results of the lubricant tests for both the 1- and 2-in.-diam specimens are reported in Table 8 and Figs. 11-14.

Table 8 Thermal resistance for lubricant tests with air

Load, lb	L	Extent of lubricant	Pressure, mm Hg	Measured resistance, °F/Btu/hr	Theoretical resistance, °F/Btu/hr
19.6 [a]	65.4	18.0	10^{-5}	10.0	10.3
			0.05	10.3	10.3
			0.6	9.1	9.6
			5.0	8.9	9.4
			20.0	9.2	9.4
			100.0	9.1	9.4
			740.0	9.1	9.4
60 [a]	450	8.7	0.05	10.4	10.6
			0.45	9.6	9.7
			1.0	9.5	9.6
			3.7	9.4	9.5
			20.0	9.4	9.4
			100.0	9.4	9.4
			400.0	9.3	9.4
			740.0	9.0	9.4
27 [b]	117.6	12.3	10^{-5}	7.0	6.6
			0.05	7.1	6.5
			0.7	6.6	5.9
			2.6	6.4	5.8
			20.0	6.3	5.7
			100.0	6.2	5.7
			400.0	6.5	5.7
			740.0	6.5	5.7
72 [b]	84.8	8.9	10^{-5}	6.7	6.9
			1.6	5.9	6.1
			20.0	5.7	6.0
			100.0	5.7	6.0
			400.0	5.9	6.0
			740	5.9	6.0

[a]Tests on 1-in.-diam ball.

[b]Tests on 2-in.-diam ball.

Table 8 shows two different load tests for each specimen as a function of the gas pressure. The pressure ranged from 10^{-5} to 740 mm Hg. Air tests only were conducted. It can be seen that the presence of a lubricant reduces greatly the effect of the contact area and the effect of the gas. In short, the lubricant is the controlling resistance in the sphere-flat contact. Figure 11 shows the lubricant test results for both specimens with air present at a pressure of 740 mm Hg. These results are compared with the air and argon tests with no lubricant present. It is seen that the overall resistance is greatly reduced because of the lubricant, and it is slightly

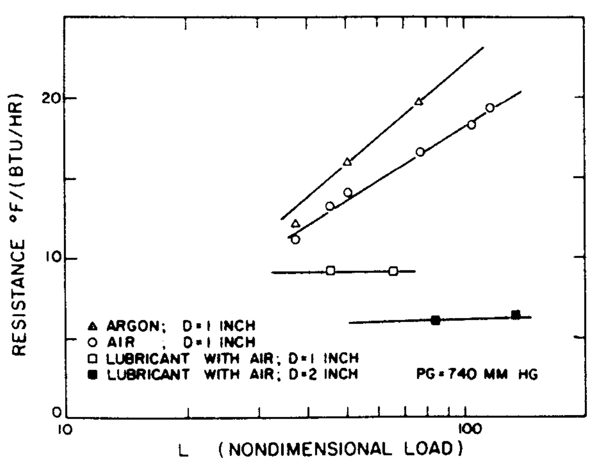

Fig. 11 Thermal resistance vs load at continuum conditions.

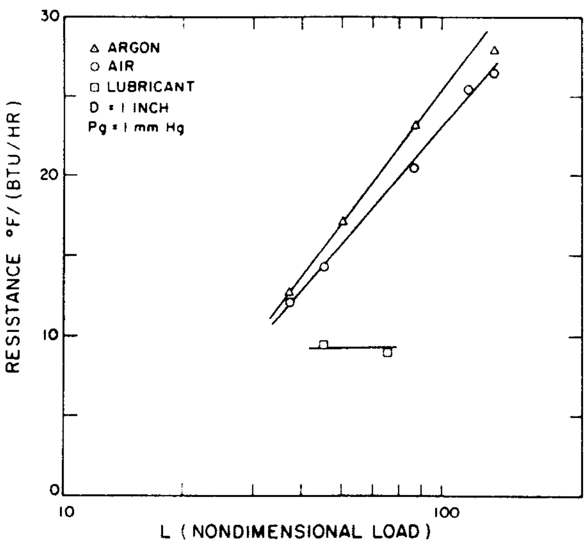

Fig. 12 Thermal resistance vs load at slip conditions.

dependent upon the load. These conditions prevail down to a pressure of 100 mm Hg.

Figure 12 shows lubricant test results for a pressure of 1 mm Hg as a function of load. The lubricant dominates the resistance, which is practically independent of load. An unlubricated contact with air or argon present at 1 mm Hg pressure is also shown for comparative purposes in Fig. 12.

In Fig. 13, we see test results for a lubricated contact having a load of 60 lb as a function of the air pressure. For comparative purposes, test results for unlubricated contacts with air or argon present are also shown for loads of 3.6 and 12.5 lb, respectively. Figure 14 shows that the effect of air pressure on a lubricated contact is negligible over the pressure range of 5×10^{-2} to 740 mm Hg.

The comparison between the test data and theoretical values[3,4] as shown in Table 8 is excellent. The lower limit for the lubricant resistance was determined by comparison between theory and test to be about 3.5 contact radii. The upper limit of the oil was determined photographically. Using a lower limit of 3.5 contact radii and the photographically determined upper limit yields excellent agreement between lu-

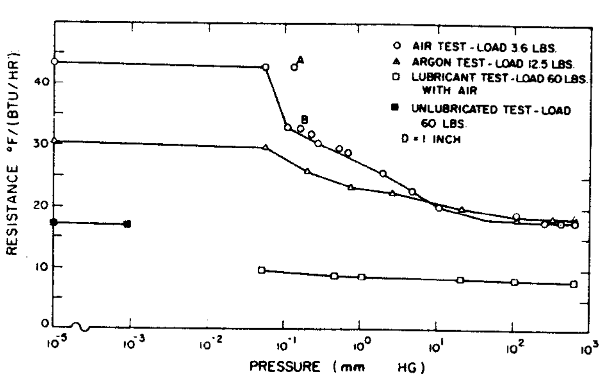

Fig. 13 Thermal resistance vs pressure at constant load.

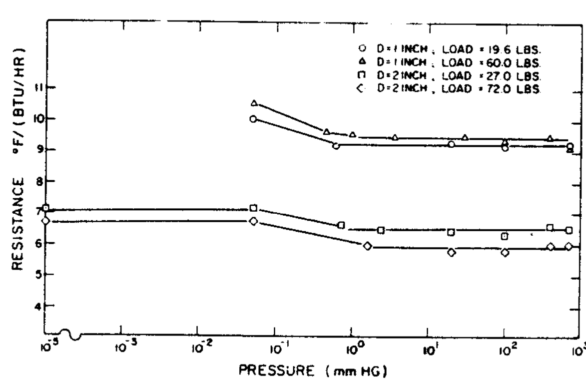

Fig. 14 Thermal resistance vs pressure at constant load.

bricated test data and theory over a wide range of gas pressures and loads.

Error Analysis

An error analysis was performed to determine the maximum percent error on the measured thermal resistance at the minimum and maximum mechanical loads for the following conditions: vacuum, rarefied, slip, and continuum. Both air and argon were examined. The error as a result of tolerances on thermocouple locations was approximately 1%. The largest maximum percent error was found to be 7.60% at the minimum load when the gas was argon in the slip regime. The average percent error for these data was estimated to be 4.65%. For all of the test data, the average percent error ranged from a low of 3.42 to 4.65%.

Summary of Conclusions

This experimental investigation has verified the hypothesis used in the theoretical work[3,4] which modeled the heat transfer across a sphere-flat contact in the presence of a gas and a lubricant. It has been shown that elasticity theory can be used to predict the overall resistance over a large load range provided that the surface roughness is equal to or less than 5 μin. (rms) and only the first loading cycle is considered. Surface roughness effects are negligible at the highest loads. Hysteresis effects have been observed due to the plastic deformation of the sphere and flat, but elasticity theory is still valid during the first loading cycle.

The decoupled model has been shown to be adequate for predicting gas and lubricant effects for the entire load range. Gas contribution to the overall resistance is strongly dependent upon loading and is very important at the highest loads. Lubricant effects are significant and independent of loading.

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