channel model have been investigated. For radially outward flow with $Re = 5.5 \times 10^3$ and $Ro = 0.24$, and transverse ribs of various sizes up to $D/e = p/e = 10$ on the leading and trailing walls, the following conclusions may be drawn:

1) For a fixed rib configuration on the leading wall, increasing the size of the ribs on the trailing wall increases the heat (mass) transfer on the leading wall.

2) For a fixed rib configuration on the trailing wall, increasing the size of the ribs on the leading wall does not significantly affect the heat (mass) transfer on the trailing wall.

3) With rotation at a relatively high speed, the heat (mass) transfer on the leading wall is quite low, regardless of the sizes of the ribs on the leading and trailing walls.

Acknowledgment

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Thermal Contact Conductance of Elastomeric Gaskets

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Introduction

REMOVING heat from electronic components is a problem faced by engineers working on thermal management issues. To a very large extent, elastomeric gaskets have replaced mica pads and silicon greases as a means for enhancing the heat transfer across a material junction. With the miniaturization of electronic components and associated increase in power densities, the thermal contact resistance across junctions has assumed significant importance. There is limited information on the thermal contact conductance of these gasket materials. To provide some information on the thermal contact conductance of elastomeric gasket materials, which would prove extremely beneficial to thermal management engineers, the present investigation was conducted.

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Fletcher and Miller[1] conducted an experimental investigation on the thermal conductance of selected filled and unfilled elastomeric gasket materials. The thermal conductance values of all the elastomers tested were lower than the conductance of the bare aluminum junction. Furthermore, the investigation concluded that elastomers with metallic or oxide fillers yielded higher conductance values than unfilled elastomers.

Scialdone et al.[2] conducted an experimental investigation to measure the thermal contact conductance of polymeric materials that are suitable for electronic systems. Thermal contact conductance of Cho-Therm 1671, a silicone elastomer, and CV-2946, a conductive RTV silicone, were measured on a test configuration that attempted to simulate heat dissipation from a modular power system. A comparison of the thermal contact conductance between the two polymeric materials indicates that the RTV silicone compound (CV-2946) had higher values than the polymeric elastomer (Cho-Therm 1671).

Mirmira et al.[3] conducted an experimental study that measured the thermal contact conductance of adhesives (epoxies, silicone elastomer, and high-temperature air-set cements). Metalbond 1146 (BASF 1146) possessed the highest thermal contact conductance value of the different adhesives investigated. Norcast 3230HT possessed the highest thermal contact conductance value among the epoxies tested. The paper concluded that the mean interface temperature and apparent interface pressure do not significantly affect the thermal contact conductance value for a majority of adhesives tested. The only exception was the silver epoxy that registered an increase in conductance with an increase in pressure. Furthermore, at higher pressures, the thermal contact conductance value of the bare junction (aluminum 6101 and aluminum 356) was higher than that with the adhesive.

Experimental Program

To provide additional information on the thermal conductance of selected thermally conductive gasket materials, an experimental investigation was conducted. Several commercially available homogeneous gasket materials commonly used in aerospace applications were selected for this study. The gasket materials were cut in the form of precise 2.54 cm (1 in.) diameter discs of different thicknesses. Table 1 lists the material properties of the gasket materials as reported by the manufacturer.

The test facility used in this experimental investigation utilized a vertical column consisting of a frame with sliding plates for the support of two combination heat source/sink specimen holder assemblies, a load cell, and pneumatic bellows. A schematic diagram of the test facility and a description has been given by Mirmira et al.[3,4]

The vertical test column consisted of aluminum 6061-T6 upper and lower flux meters and a central aluminum 6061-T6 sample. The diameter of the flux meters and the sample were 2.54 cm (1 in.) and the lengths were 10.16 cm (4.0 in.) and 3.81 cm (1.5 in.), respectively. The thermally conductive gasket was placed at the interface between the aluminum 6061 central sample and the aluminum 6061 flux meter. The flux meters were instrumented with 30-gauge, Teflon/Teflon® sheath, special limit of error, K-type thermocouples.

Experimental Procedure

The aluminum 6061 flux meters and sample with the gasket positioned in between were inserted carefully into the test facility and aligned. The heat fluxes in the upper and lower flux meters as well as through the sample and gasket were determined by knowing the temperature gradients and thermal conductivities of the aluminum 6061 heat flux meters and sample. The difference in temperature at the gasket—flux meter interface was determined by extrapolating the temperature gradient in the heat flux meters to the gasket interface. The apparent interface pressure at each temperature was varied according to the hardness (Shore A) of the gasket being tested.

Table 1 Thermophysical properties, thickness, and characteristics of selected elastomeric gasket materials

Product designation	Thermal conductivity, W/mK	Thermal resistance (m^2K/W)	Hardness (Shore A)	Specific gravity	Thickness, mm	Fiberglass support
Grafoil GTA	——	——	——	——	0.125, 0.375, 0.750	No
Abletherm 5130	2.90	——	80	2.30	0.381	No
Cho-Therm 1671	2.60	14.8E-05	90	1.55	0.381	No
Cho-Therm 1674	1.00	26.0E-05	90	1.60	0.254	Yes
Cho-Therm 1678	1.60	15.0E-05	90	1.60	0.254	Yes
Cho-Therm 1680	0.70	27.1E-05	10	1.50	0.178	No
Cho-Therm T500	2.70	12.0E-05	95	1.55	0.254	Yes
Cho-Therm A274	——	23.0E-05	——	2.00	1.020	Yes
T-dux OC	——	20.0E-05	——	2.20	1.020	Yes
T-pli 210	6.00	7.09E-05	10	1.28	0.254	No
T-pli 220	8.00	9.03E-05	10	1.28	0.508	No
T-pli 220	8.00	9.03E-05	10	1.28	0.508	Yes
T-pli 230	8.00	13.55E-05	10	1.28	0.762	No
T-gon 220	6.00	12.90E-05	76	——	0.508	Yes
T-flex 220	6.00	——	10	——	0.254	No
E7-49-OC-NFG	6.00	——	10	——	0.508	No
E7-52F-OC	6.00	——	10	——	0.508	No
Silicone elastomer (Ag coated with Cu)	——	——	——	3.84	0.712	No
Silicone elastomer (Ag flakes)	——	——	——	1.90	0.710	No

Uncertainty Analysis

The uncertainty involved in the various parameters and quantities used to compute the thermal contact conductance can be combined to arrive at one overall relative uncertainty value. The Kline and McClintock[5] method was employed to determine this overall uncertainty in the thermal contact conductance.

The overall uncertainty in the thermal conductivity for the aluminum 6061 material was 2.5%, which consisted of the uncertainty in the temperature reading of the special limit of error flux meter and location tolerance of the thermocouple holes and dimensional tolerance for the cross-sectional area. The total average uncertainty in the thermal conductance value for each gasket material tested was approximately 8.0%.

Results and Discussion

The experimental investigation of the thermal contact conductance of the thermally conductive gaskets (1 in. diameter) employed between aluminum 6061 surfaces was conducted at 20 and 80°C (68 and 176°F) and under uniform pressure that ranged from 172 to 6890 kPa. The thermal contact conductance results of the gaskets tested are presented as a function of apparent interface pressure. Figure 1 shows the thermal conductance of T-pli materials, which have a relatively low Shore A hardness when compared to T-gon materials, and were thus tested under a pressure cycle that ranged from 172 to 2067 kPa (25 to 300 psi). The thermal conductance values of all these gasket materials increase with an increase in pressure. This may be attributed to the fact that the gasket material is squeezed and decreases in thickness with an increase in applied pressure. Furthermore, the gasket materials demonstrate a hysteresis, that is, the conductance value was higher during the decreasing pressure cycle when compared to the increasing pressure cycle (except for the grafoil samples). Although, T-pli 210 (thickness = 0.25 mm) is half as thick as T-pli 220 (0.5 mm), both materials have similar thermal conductance values. This may be attributed to T-pli 210 possessing a lower thermal conductivity (6 W/m K) than T-pli 220 (8 W/m K). Figure 1 also indicates that the thermal conductance value of the T-pli 220 gasket material supported with fiber glass is lower than unsupported T-pli 220. The fiberglass filler possibly enhances the mechanical properties, but may also lower the thermal properties. The T-gon 220 gasket material with a Shore A hardness of 76 was tested under a pressure cycle ranging from 172 to 4134 kPa (25 to 600 psi). T-gon 220 possesses a lower

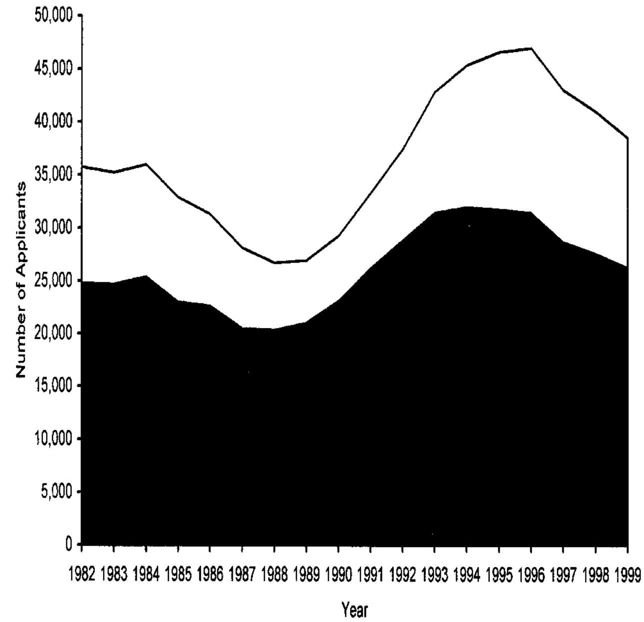

Fig. 1 Thermal contact conductance of T-pli, T-gon, and bare aluminum as a function of apparent interface pressure.

thermal conductivity value compared to the T-pli materials and, hence, has a lower conductance value at the same applied interface pressure. The change in mean interface temperature from 20 to 80°C does not appear to significantly affect the thermal conductance value for these gasket materials. Figure 1 also indicates the thermal contact conductance of a bare aluminum 6061 (T6) junction. It is evident that all the gasket materials (except T-gon 220, fiberglass supported above 2000 kPa) provide a better conductance value than the bare aluminum junction.

Figure 2 shows the thermal contact conductance for GTA Grafoil specimens and Cho-Therm specimens as a function of apparent interface pressure ranging from 172 to 4134 kPa (25 to 600 psi). GTA Grafoil materials of 0.125, 0.375, 0.75 mm in thickness possessed thermal conductance values ranging from 4300 to 6900 W/m^2K and 7600 to 14,300 W/m^2K, respectively. On the other hand, the GTA Grafoil sample of 0.125 mm in thickness had the highest thermal conductance

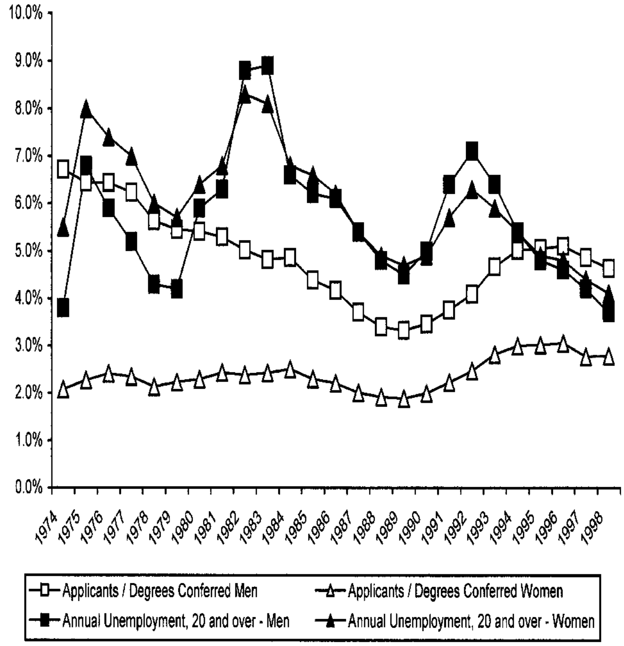

Fig. 2 Thermal contact conductance of Cho-Therm, T-dux, and bare aluminum as a function of apparent interface pressure.

values ranging from 13,400 to 32,000 W/m^{2}K. Compared to the T-pli gasket materials tested, the Cho-Therm gasket materials possessed a higher Shore A hardness and were consequently subjected to a pressure range of 172–4134 kPa (25–600 psi). The overall thermal conductance for these gasket materials ranged from 800 to 8700 W/m^{2}K over the range of pressures and thickness. Cho-Therm 1671 and Cho-Therm T500 have the highest thermal conductivity. Consequently, a comparison of materials of equal thickness indicates that Cho-Therm 1671 and Cho-Therm T500 have higher thermal conductance values.

The thermal contact conductance as a function of apparent interface pressure for Abeltherm 5130, T-dux OC, E7-49-OC-NFG, and E7-52F-OC are also shown in Fig. 3. Abeltherm has a lower thermal conductance value as compared to Cho-Therm 1671, for the same material thickness. Comparing the thermal contact conductance of the gaskets with the bare aluminum 6061 (T6) junction, it is evident that below 2500 kPa the bare aluminum junction has a thermal conductance value below that of the gasket materials, but above 2500 kPa the conductance value of the bare junctions exceeds that of the gaskets.

Figure 3 shows the thermal conductance as a function of applied apparent interface pressure for seven additional gasket materials. These gasket materials have a lower conductance value when compared to the gasket materials depicted in Fig. 3; consequently, the thermal contact conductance of bare aluminum junction exceeds that of the gasket junction at approximately 1500 kPa. The Cho-Therm A274 sample was significantly thicker when compared to the other materials and, thus, the thermal conductance associated with this material was lower. Cho-Therm 1678 has a higher thermal conductivity when compared to Cho-Therm 1680 and Cho-Therm A274 and, thus, it possesses a higher thermal contact conductance over the pressure range investigated. The temperature of the interface also does not appear to greatly influence the thermal conductance value for these materials as well.

The last two gasket materials to be tested were silicone elastomers that contained either inert particles or flakes in the matrix or possessed a metallic coating. Figure 3 shows the thermal conductance of these gasket materials as a function of applied interface pressure. The thickness of these gasket materials significantly influences the thermal conductance value. The silicone elastomers with silver-coated copper powder and silver

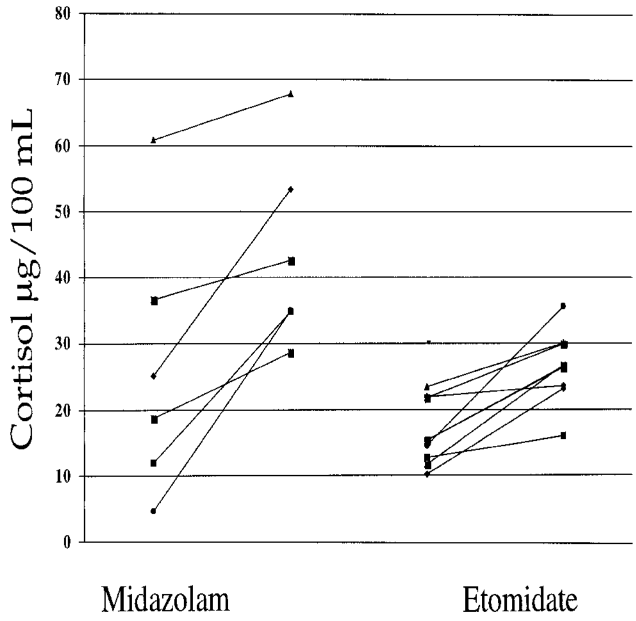

Fig. 3 Thermal contact conductance of Cho-Therm and T-flex as a function of apparent interface pressure.

flakes had conductance values ranging from 500 to 1200 W/m^{2}K over the specified pressure range. It is interesting to note that for these gasket materials the conductance values do not change as much with pressure when compared to the gasket materials previously discussed. A possible reason for this is that these materials are stiffer and do not compress under load and do not decrease in thickness, which would lead to an increase in thermal conductance for some of the softer gasket materials.

Conclusions and Recommendations

This Note provides a comparative study of the thermal contact conductance of a large number of commercially available thermally conductive gaskets over a wide range of temperatures and pressures encountered in aerospace applications. The experimental data obtained indicate that the thermal conductance of the gasket material is not significantly affected by these interface temperatures, but at higher temperatures the material composition may change, resulting in a degradation of the conductance. Further, higher interface pressures result in higher conductance values. Considering the fact that a majority of these gaskets are squeezed with an increase in applied interface pressure, resulting in an increase in thermal conductance value, it would be beneficial to incorporate a linear variable differential transducer to measure the subtle changes in the thickness. Furthermore, the effect of the chemical composition on the thermal conductance of these gasket materials should be investigated.

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