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Technical Note

Gap conductance in contact heat transfer

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Abstract

At low contact pressures, conduction across the gas gap is the predominant mode of heat transfer in a joint. Experimental results are presented for the solid spot and the gap conductance for a range of surface finishes and several interstitial gases and gas mixtures. The mean separation distance is then estimated as the difference between the effectiive gap thickness and the temperature jump distance. It is seen that a simple relation exists between the mean separation distance and surface roughness for all the gases and gas mixtures. This correlation satisfies 85% of data points to within ±4%.

Keywords: Thermal contact conductance; Gas gap conductance; Surface roughness; Mean separation distance; Temperature jump

1. Introduction

Engineering surfaces are never absolutely smooth and surface irregularities are apparent when observed under a microscope. As a result, when two solids are pressed together, contact is made only at a few discrete points separated by relatively large gaps. Due to the reduction in heat transfer area at the interface of two solids, there exists an extra resistance to heat flow. Heat flow across the interface can take place by means of conduction in solid-to-solid contact spots and conduction across the gas gap. Conduction across the gas gap is particularly important if:

(a) the contact pressure is relatively low [2], and/or
(b) the interface medium is a relatively good conductor.

Radiation also needs to be considered at temperatures higher than 300°C [1].

Thermal contact conductance is defined as the ratio of heat flux across the joint to the additional temperature drop due to the imperfect contact at the interface.

Literature reviews indicate that, there exists a substantial amount of data on the solid spot conductance [3,4]. However, there is comparatively little information on gap conductance, especially of an experimental nature. Further, most of the previous works on gap conductance deal with single gases.

The present work deals with experimental measurements of conductance across the gap filled with either a single or a mixture of gases. The interface fluids used were helium, argon, carbon dioxide, nitrogen and mixtures of argon and helium. It also proposes a correlation for the estimation of the gap conductance.

2. Background

In heat transfer across small gaps, the "temperature jump distance" must be taken into account. If g_1 and g_2 are the temperature jump distances for surfaces 1 and 2, respectively, then the gas gap conductance may be defined as:

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Nomenclature

C	specific heat
g	temperature jump distance
h	thermal conductance across the interface
k	thermal conductivity of the gas
m	mass fraction of the gas
M	molecular weight
P	gas pressure
R_0	universal gas constant
R_p	maximum peak height
R_q	effective rms surface roughness, $\sqrt{(R_{q_1}^2 + R_{q_2}^2)}$
T	interfacial temperature
x	molar fraction of the gas

Greek symbols

α	accommodation coefficient
δ	mean separation distance
γ	specific heat ratio

Subscripts

1, 2	surfaces 1 and 2
eff	effective
g	gap
mix	gas mixture
p	constant pressure

$$h_g = \frac{k_g}{(\delta_{eff})} \tag{1}$$

$\delta_{eff} = \delta + g_1 + g_2$, and δ is the mean separation distance.

Temperature jump distance of a single gas is given by Kennard [5].

$$g = \frac{k}{P}\left(\frac{2-\alpha}{\alpha}\right)\left(\frac{2\pi T}{R}\right)^{1/2}\left(\frac{\gamma-1}{\gamma+1}\right) \tag{2}$$

Thermal conductivity of the gases used in the experiments are estimated from the following correlations:

Helium [6]: $$k_{He} = 3.36 \times 10^{-3} \times T^{0.668} \tag{3a}$$

Argon [6]: $$k_{Ar} = 3.421 \times 10^{-4} \times T^{0.701} \tag{3b}$$

Carbon dioxide [2]:

$$k_{CO_2} = 8.1 \times 10^{-5} \times T - 0.0075 \tag{3c}$$

Nitrogen [7]:

$$k_{N_2} = 0.025 + 5.84 \times 10^{-5} \times (T - 273) \tag{3d}$$

For an interfacial gas mixture, Eq. (2) is modified as

$$g_{mix} = \frac{k_{mix}}{P}\left(\frac{2-\alpha_{mix}}{\alpha_{mix}}\right)\left(\frac{2\pi T}{R_{mix}}\right)^{1/2}\left(\frac{\gamma_{mix}-1}{\gamma_{mix}+1}\right) \tag{4}$$

in which the thermal conductivity of mixtures of gases are estimated from [8]

$$k_{mix} = \sum_{i=1}^{n} \frac{k_i}{1 + \sum_{\substack{i=1 \\ j\neq i}}^{n} \Phi_{ij}\frac{x_j}{x_i}} \tag{5}$$

where

$$\Phi_{ij} = 0.3765\left(1 + \frac{M_i}{M_j}\right)^{-1/2}\left[1 + \left(\frac{k_i}{k_j}\right)^{1/2}\left(\frac{M_i}{M_j}\right)^{1/4}\right]^2$$

Song and Yovanovich [9] developed correlations for the accommodation coefficients for helium and argon. These correlations were based on the results of previous workers over the period 1950–1982. In the present work, the accommodation coefficient for any mixture was estimated by linear interpolation.

From classical thermodynamics [10]

$$\gamma_{mix} = \frac{C_{p_{mix}}}{C_{v_{mix}}}$$

$$f_{mix} = \sum \frac{m_i}{m} f_i \tag{6}$$

in which f is the property such as R, C_p or C_v and m_i/m is the mass fraction of the gas and $R = R_0/M$.

3. Experimental program

3.1. Experimental setup

The experiments were conducted in an axial heat flow cut bar apparatus. A schematic diagram of the experimental set up is shown in Fig. 1. The experimental rig consists of heater block, reference heat flux meters, upper and lower specimens and a heat sink. A band type heater provides maximum heat input of 80 W.

The heat flux meters are made from special reference material RM 8421, supplied by the National Institute of Standards and Technology, USA. The heat sink is a hollow copper cylinder. Cooling is accomplished by chilled water circulating through the heat sink. The test column is enclosed inside a glass cylinder that sits on stainless steel base plate. Stainless steel bellows are used to facilitate vertical movement of the column. The top plate sits on the glass cylinder. Load can be applied to the test column by a hanging weight arrangement. A diaphragm type valve is provided to facilitate the gas introduction. The chamber is evacuated by an oil sealed rotary vane pump. Temperature measurements are made by fourteen type K thermocouples. The data acquisition set up is composed of two 8 channel ADAM, 4018 analogue/thermocouple input modules, one ADAM RS 232 to RS 422/RS 485 converter, and a computer.

3.2. Test specimens and gases

The stainless steel AISI 304 specimens and heat flux meters were machined to cylindrical shape having diameter 18 mm and length 25 mm. Each specimen had three holes of 1 mm diameter and 9 mm depth for locating thermocouples. The holes were 7 mm apart from the first one and 5.5 mm from the contact surface. The contact surfaces were first polished with a 3 μm diamond polish. The surfaces were cleaned using acetone and then bead blasted. Surface measurements were made with a Talysurf 4 and a PC installed with A/D card. Typically 11 traces were randomly selected. Table 1 lists the RMS roughness of the test specimens and mixture ratio of the interfacial gases.

3.3. Experimental procedure

The specimens were insulated with two half cut

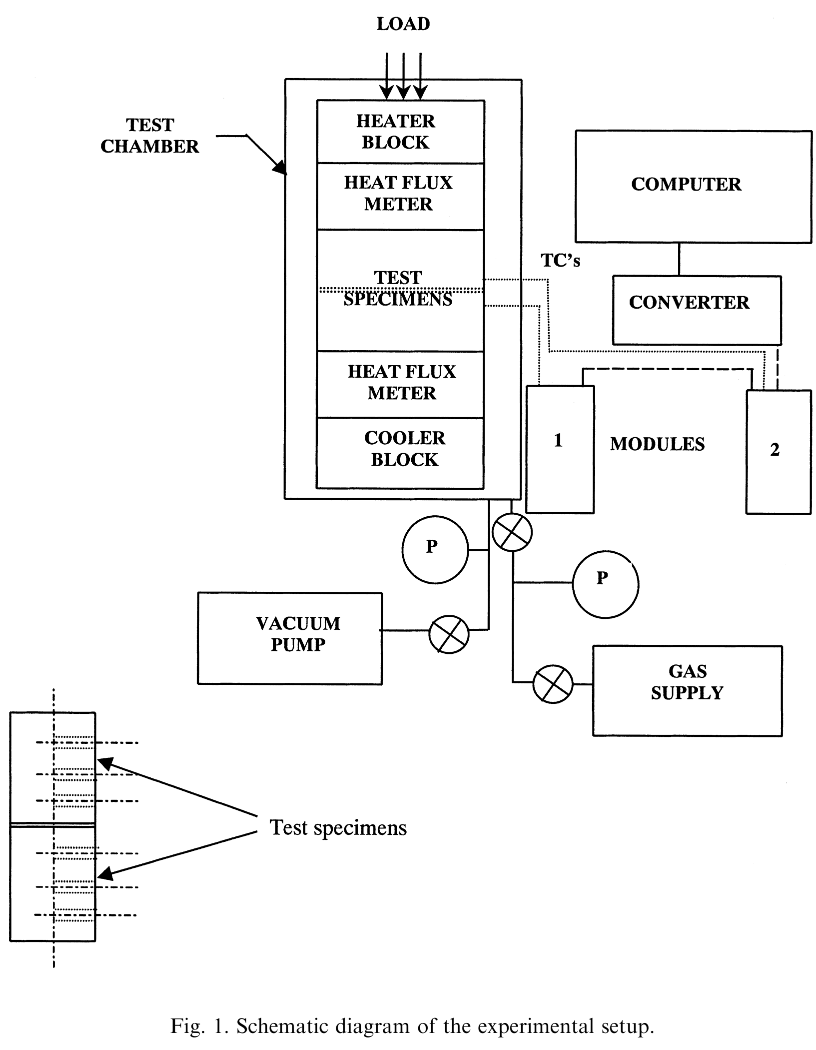

Fig. 1. Schematic diagram of the experimental setup.

Table 1
The interfacial medium and the roughness of the stainless steel (AISI 304) surfaces

Interfacial gas or gas mixture							R_q (μm)
He	He:Ar	He:Ar	He:Ar	Ar	N_2	CO_2	
100	75:25	50:50	25:75	100	–	–	5.4
100	75:25	50:50	25:75	100	100	100	14.3
100	75:25	50:50	25:75	100	100	100	21.2

Teflon tubes having a clearance of 1 mm. Grooving was provided to facilitate thermocouple wires to be inserted on the specimens. The Teflon tube itself was insulated with Kao Wool Blanket, and the gap between the Kao Wool blanket and the Teflon was filled up with glass wool.

Thermal conductivity of the test specimens was first established by comparing the heat flux through the specimens with that measured by the heat flux meters.

The tests were conducted at a contact pressure of 0.433 MPa in the following order:

- Tests in vacuum (3×10^{-2} mbar) to determine the solid spot conductance.
- Series of tests with interfacial gases at an average gas pressure of 0.12 MPa, that is, slightly above atmospheric pressure.
- Repeat of tests with different RMS roughness.

Pure helium and argon were mixed according to a process described by Wahid et al. [11]. The conductance measurements were made over a range of mean interfacial temperatures from 30° to 95°C. The surface temperature at the interface was obtained by extrapolating the temperature readings in each specimen using the method of least squares.

The errors in the experiments include the heat losses from the specimens, uncertainties in the location of the thermocouples, the conductivity of the materials and the calibration of thermocouples. The overall experimental uncertainty in this experimental procedure was estimated to range from 3 to 12% depending on whether tests were conducted in vacuum or a conducting environment.

4. Experimental results and discussion

The gap conductance was determined as the difference between the total conductance and the solid spot conductance.

The temperature jump distances were determined from Eqs. (2) and (4). Conductivity of the gases was evaluated using Eqs. (3) and (5). Then, for each case, δ_{eff} was determined from the measured values of gap conductance, using Eq. (1). The mean separation distance, δ, was found by subtracting the sum of temperature jump distances for the two surfaces from δ_{eff}. The mean separation distance was non-dimensionalised by dividing it by the combined surface roughness.

The results are plotted in Fig. 2. The following simple correlation is evident from the plot:

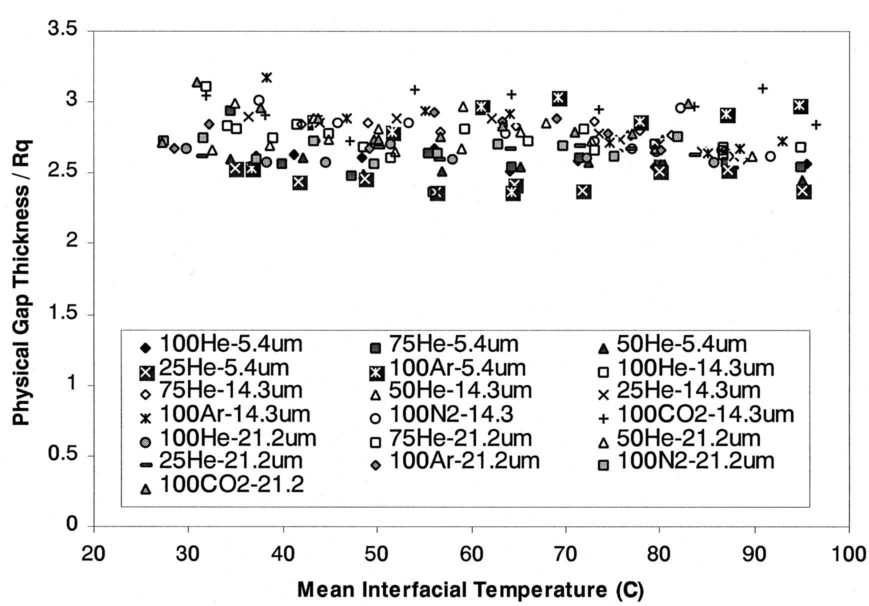

Fig. 2. Gap separation distance for a range of gases.

$$\delta \approx 2.7\ R_q \tag{7}$$

It is noted that 85% of the experimental results (173 data points, three different surface roughnesses and seven different gases and gas mixtures) fall within $\pm 4\%$ of this correlation.

It is instructive to compare this correlation with the approximate correlation due to Song et al. [12].

$$\delta \approx R_p \tag{8}$$

However, the correlation of Eq. (8) applies specifically to the contact of a rough surface with a smooth surface at light load and R_p refers to the rough surface only. Also, the temperature jump distances have not been separately identified. Note that the relationship between R_p and R_q depends on the type of surface finish.

5. Conclusions

1. Gap conductance data for a range of interfacial gases were generated experimentally.
2. The effective gap thickness at the interface was determined experimentally, and the mean separation distance was deduced from subtracting the temperature jump distance from the effective gap thickness.
3. A simple relation was found to exist between the mean separation distance and surface roughness for all the gases and gas mixtures. This correlation is shown to be very good, satisfying 85% of data points to within $\pm 4\%$.

Acknowledgements

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References

[1] C.V. Madhusudana, in: Thermal Contact Conductance, Mechanical Engineering Series, Springer-Verlag, New York, 1996, pp. 1–6.

[2] C.V. Madhusudana, Thermal contact conductance and rectification at low joint pressures, International Communications in Heat and Mass Transfer 20 (1) (1993) 123–132.

[3] B. Snaith, S.D. Probert, P.W. O'Callaghan, Thermal resistances of pressed contacts, Applied Energy 22 (1) (1986) 31–84.

[4] M.A. Lambert, L.S. Fletcher, Review of models for thermal contact conductance of metals, Journal of Thermophysics and Heat Transfer 11 (2) (1997) 129–140.

[5] E.M. Kennard, in: Kinetic Theory of Gases, McGraw-Hill, New York, 1938, pp. 311–324.

[6] J.M. Gandhi, S.C. Saxena, Correlated thermal conductivity data of rare gases and their binary mixtures at ordinary pressures, J. of Chem. and Engr. Data 13 (3) (1968) 357–361.

[7] A.A. Hegazy, Thermal contact conductance of rough surfaces: effect of surface micro hardness variation, Ph.D Dissertation, Department of Mechanical Engineering, University of Waterloo, Waterloo, Ont., Canada, 1985.

[8] E.A. Mason, S.C. Saxena, Approximate formula for the thermal conductivity of gas mixtures, Physics of Fluids 1 (5) (1958) 361–369.

[9] S. Song, M.M. Yovanovich, Correlation of thermal accommodation coefficient for engineering surfaces, ASME HTD 69 (1987) 107–116.

[10] E.A. Eastop, A. McConkey, in: Applied Thermodynamics for Engineering Technologists, Longman, New York, 1970, pp. 433–463.

[11] S.M.S. Wahid, C.V. Madhusudana, E. Leonardi, An investigation of the effect of gases on thermal gap conductance at low contact pressures, in: J.S. Lee (Ed.), Proceedings of the 11th International Heat Transfer Conference, vol. 7, Taylor & Francis, Philadelphia, PA, 1998, pp. 95–100.

[12] S. Song, M.M. Yovanovich, F.O. Goodman, Thermal gap conductance of conforming surfaces in contact, ASME Journal of Heat Transfer 115 (1993) 533–540.