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Technical Note

Numerical analysis of heat flow in contact heat transfer

Syed M.S. Wahid *

School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney 2052, Australia

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Abstract

A finite difference analysis of heat conduction problem in a cylinder terminating in a frustum of a cone is presented. The constriction can be either in vacuum or in a gaseous environment. A fine mesh of 2500×800 was used for the construction of the grid such that very small constrictions could be analysed sufficiently accurately. Small constrictions i.e., small contact areas separated by large voids filled with a gas are typical of most practical applications involving contact heat transfer. The result of the finite difference analysis shows that gap conductance is predominant for all the gases considered. Gap-to-solid conductance ratio increases as the cone angle decreases due to the decrease of gap thickness. It also indicates that increase of conductance ratio is less significant at higher constriction angles. Finally, predicted conductance parameters are compared with the experimental results for different interfacial gases and a very good agreement is obtained.

Keywords: Gap conductance; Solid spot conductance

1. Introduction

It is well known that when two surfaces are in contact, the contact surface profile plays an important role in the heat flow across the interface. In any contact heat transfer application the contact is made only at a few discrete spots separated by large gaps. In most engineering applications, joints of two surfaces will generally be in a gaseous environment. Heat transfer across a joint can take place by conduction through the actual contact spots, conduction through the gaseous medium at the joint and radiation across the gap. In the present analysis radiative heat flow will not be considered since it is only significant at high temperature [1]. Total conductance at the joint, therefore, is the sum of conductance through the gaseous medium and solid contact spots. This thermal conductance can be defined as the ratio of the heat flux to the temperature drop at the interface.

Centinkale and Fishenden [2] considered that the contact spots to be cylindrical surrounded by fluid of uniform thickness. The isotherms and heat flow lines were assumed to be ellipses and hyperbolas respectively.

Extending the work of Centinkale, Fenech and Rohsenow [3] considered following approximations in their constriction analysis.

1. All the contact points are of equal size and evenly distributed.
2. The heat channel associated with each contact point and through the gas was taken as cylindrical and axial.

The previous works answer that either: (a) the constriction was a plane circular area, or (b) a circular cylinder of height equal to mean gap thickness. It is clear from surface analysis, however, that the slope of the constriction is conical.

Madhusudana [4], therefore, considered heat flow through conical constrictions and presented results of the finite difference solution of heat conduction. A grid size of 101×41 was used in his analysis. The results indicated that constriction resistance decreases with the increase of the ratio of constriction and cylinder in both vacuum and gaseous environment. His analysis also

* Tel.: +61-2-9385-6271; fax: +61-2-9663-1222.
E-mail address: s.wahid@unsw.edu.au (S.M.S. Wahid).

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Nomenclature

a	radius of contact spot
b	radius of feeding cylinder
h	joint conductance
k	thermal conductivity
L	length of cylinder
m	effective profile slope
n	normal direction
Q	total heat transfer per unit area
Rq	effective rms roughness height
Greek symbols	
β	cone angle
Δr	length of radial side
ΔT	temperature drop
Δz	length of axial side
Subscripts	
1,2	surfaces 1 and 2
g	gas
s	solid

indicated that in vacuum environment, constriction resistance decreases as cone angle reduces.

Olsen et al. [5] presented a numerical analysis to determine the constriction resistance at an individual spot. Coated and uncoated metallic joints were used in vacuum and gaseous environment. Ratio of contact spot radius to that of the radius of heat flux tube (a/b) ranged from 0.1 to 0.4, suggesting a relatively smooth surface, thus a grid of 201×51 element grid was used to solve the problem. It was reported that an improvement of constriction resistance was achieved with metallic coatings whereas the presence of gas slightly reduced the constriction resistance. However conduction across the gas gap is particularly important if the contact pressure is relatively low (i.e., contact is made only at a few discrete points separated by relatively large gaps) and the interface medium is relatively good conductor [6,7].

It thus necessitates developing a numerical analysis to evaluate the effect of interfacial gases on the joint conductance at a low a/b, implying the existence of large interfacial gaps. This also needs to be validated by actual experimental results.

The present author has considered conical constrictions and assumed that all the contact points are of equal size and are evenly distributed and describes the results of finite difference solution of joint conduction problem with the boundary conditions as shown in Fig. 1.

2. Method of analysis

The conducting media is divided into a grid consisting of axial and radial mesh points. The cylinder is divided into a number of zones as given in Fig. 1. The heat flows from the top of the cylinder to the bottom at constant temperature of 73 and 34 °C respectively. A modified version of the program of Madhusudana [4] was used to solve the problem. The resulting equations are solved by the Gauss–Sidel method with successive over relaxation. Heat flux in and out of the domain is

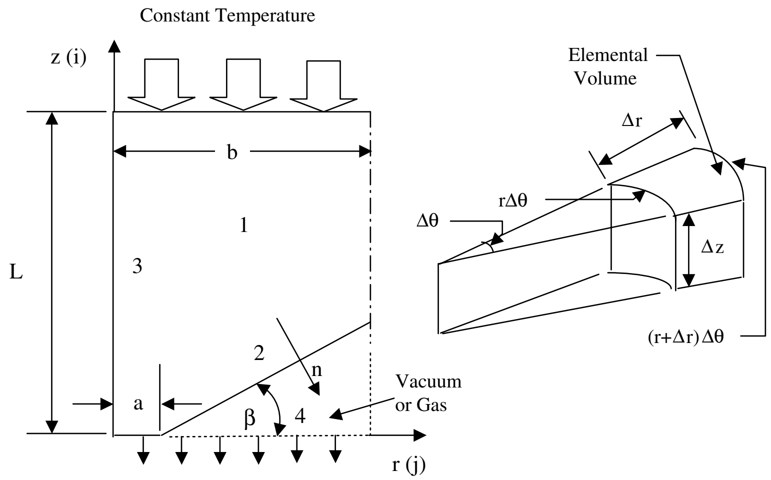

Fig. 1. Heat flow through a cylinder.

within 3%. A mesh of 2501×801 was used in all the computations as a compromise between computational effort and accuracy required. The finite difference network at each point is obtained by performing an energy balance on the elemental volume surrounding that point as shown in Fig. 1.

Boundary conditions

$$\frac{\partial T}{\partial r} = 0 \quad r = 0, \ 0 \leqslant z \leqslant L$$

$$\frac{\partial T}{\partial r} = 0 \quad r = b, \ 0 \leqslant z \leqslant L$$

$$T = \text{constant}, \quad z = L, \ 0 \leqslant r \leqslant b$$

$$k_s \frac{\partial T}{\partial n} = k_g \frac{\partial T}{\partial n}, \ \text{solid/gas boundary}$$

where a is the radius of the contact spot, b is the radius of the feeding cylinder, L is the length of the cylinder, β is the angle of the cone and n is the normal direction.

3. Results and discussion

In each case, the temperature profile obtained from the numerical solution is examined to confirm that the solution indeed represents the physical situations shown in Fig. 1. The influence of semi-angle at the joint and thermal conductivity of gases on joint conductance is shown in Figs. 2 and 3 respectively. In particular the results indicated that:

- the influence of gas gap conductance is predominant for the whole range of gases considered,
- conductance ratio increases as $\tan\beta$ decreases due to the decrease of gap thickness,
- increase of conductance ratio is less significant at higher semi-angle.

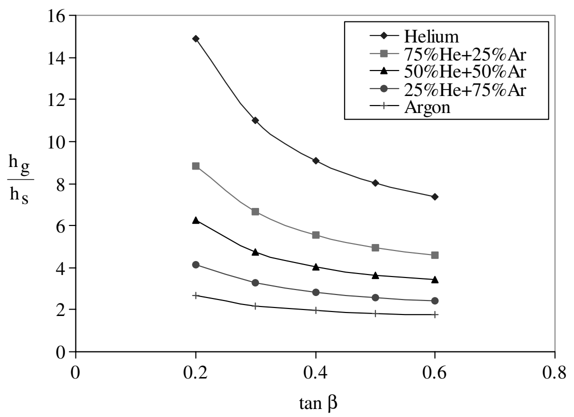

Fig. 2. Conductance ratio (gas gap to solid spot conductance) and $\tan\beta$ for a range of interstitial gas mixture of helium and argon.

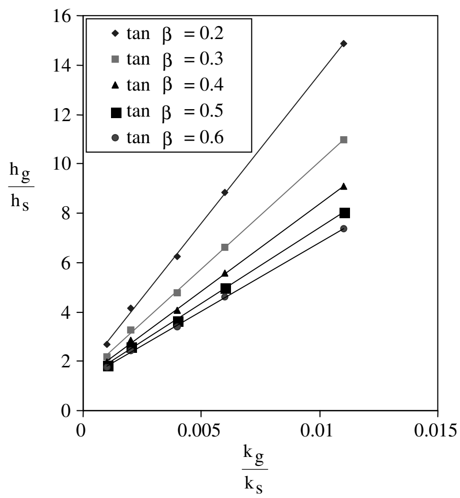

Fig. 3. Conductance ratio and gas conductivity ratio for a range of interstitial gas mixture of helium and argon.

Experimental analysis of thermal conductance was conducted by the author and the results reported elsewhere [7]. In particular, experiments were performed to measure gas gap conductance of AISI stainless steel 304 pairs over a range of mean interfacial temperatures.

For tests in vacuum, the vacuum level was maintained at 3.0×10^{-2} mbar. For all tests in gaseous environment, gas pressure was maintained within 0.114 and 0.130 MPa and the contact pressure was kept at 0.466 MPa. The interstitial gases and gas mixtures used were pure helium, pure argon, and mixtures of helium and argon. Table 1 lists the surface characteristics of the test materials. The actual surface characteristics of the stainless steel AISI 304 pairs and the properties of the gases employed at the interface of the pairs are given in Table 1.

Table 2 compares the measured total joint conductance of AISI 304 stainless steel pairs of rms roughness height 21.2 μm at a radius ratio of 0.00625, specifically, for helium, mixture of 50% helium and 50% argon, and pure argon at a mean junction temperature of 34 °C. The results indicate that the model yields excellent results. The deviations are 14.8%, 6.1% and 16.8% respectively. Finite difference method approximation is only valid for an infinite or very large value of height as shown in Fig. 1, to get an uniform heat flux at the top. It is also to be noted that the comparison between numerical analysis and experimental data is based on the assumption that cone angle of $\tan\beta = 0.6$ to be equal to the actual measured effective slope m of the test specimen where $m = \sqrt{m_1^2 + m_2^2}$. This would contribute to some discrepancy between the theory and the experiment.

Table 1
Surface characteristics of the test specimens and interfacial gases

Surface roughness height Rq (μm)			Mean slope m (radians)
Rq1	Rq2	Effective Rq	
14.73	15.25	21.2	0.601
Percentage of interfacial gases between stainless steel specimens			
Vacuum	He	He:Ar	Ar
	100	50:50	100

Table 2
Comparison of the numerical results with that of the experimental gap conductance

Environment	Experimental h_T (W/m^2 K)	Numerical h_T (W/m^2 K)	% Difference
Helium	2946.9	2511.3	14.8
50% helium + 50% argon	1237.69	1161.5	6.1
Argon	516.84	604.2	16.8

4. Conclusions

Numerical solutions, by finite difference method, have been developed for problems in heat flow through constrictions in gaseous environment. Temperature profiles have been obtained for problems in heat flow through conical constriction. Results show good agreement with experimental results conducted by the author. In particular the result shows that:

1. Gas gap conductance through an interface is a significant parameter for smooth or rough surfaces at low contact pressure applications or at low radius ratio.
2. Increase of conductance is less significant at higher semi-angle.
3. Conductance ratio increases as cone semi-angle decreases due to the decrease of gap thickness.

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