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# DISCUSSION

## L. S. Fletcher[2]

The authors have utilized dimensional analysis in the formulation of correlation parameters for the estimation of thermal contact conductance in a vacuum. Such an approach has been used before, but the results usually have not met with as much success as the correlation parameters of the present work. An analysis of this type, however, should indicate the limitations of the correlation parameters so that they will not be generalized beyond their limits of application.

Although the paper discusses some of the previous work on the correlation of thermal contact conductance, several of the more extensive correlation investigations have been omitted. In particular, the work of Laming [30], Hsieh and Touloukian [31], Fletcher [32, 33], and Malkov [34] should be considered in a discussion of the correlation of thermal contact conductance. In addition, Fried [35] has recently critically reviewed correlation and prediction techniques for thermal contact conductance, and established some guidelines for the correlation and prediction of the contact conductance of a joint. It would have been instructive had the authors compared their correlation expressions and techniques to those of other investigators.

One of the recently developed correlation expressions [33] complements the present work but includes an additional parameter for compensation of the variation of mean junction temperature. The correlation parameters were dimensionless conductance $C\delta/Ak$ and dimensionless contact load $(W/AE)\beta T_m$. The surface parameter $\delta$ represented flatness deviation and roughness deviation of both surfaces, and the apparent contact pressure was made dimensionless with the modulus of elasticity $E$. The mean junction temperature $T_m$ was made dimensionless with the coefficient of thermal expansion $\beta$ for the material. These parameters were found to correlate both high- and low-mean-junction-temperature aluminum, stainless steel, brass, and magnesium experimental conductance data [32] on one dimensionless curve.

An analysis of some selected data (both ground and sanded surfaces [18, 32]) in terms of the present correlation parameters indicated the probable importance of mean junction temperature to the correlation of thermal-contact-conductance data. Although these data demonstrated reasonable agreement, lower-temperature data for the same surface contacts and apparent contact pressure were further removed from the correlation curves. It would appear, then, that the inclusion of the effect of mean junction temperature would lead to even more successful correlation parameters.

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## W. M. Rohsenow[3] and B. B. Mikic[4]

Dimensional analysis can lead to deceiving results. The problem in this paper is that the quantities $C\ (= q/\Delta T)$ and $W$ are used as significant variables instead of $h = C/A = (q/A)/\Delta T$ and pressure $p = W/A$. The difference is the $A$ in each denominator. Surely $q/A$ and $p$ are more appropriate quantities for this work than $q$ and $W$.

Using the quantities $h$, $\sigma$, $k$, $p$, and $M$, dimensional analysis leads to the groups

$$\frac{h\sigma}{k} \quad \text{and} \quad \frac{p}{M}$$

equally valid from dimensional analysis, but much better physical quantities. The mean slope $\psi$ is dimensionless, so dimensional analysis cannot tell us where it belongs; however, the theory as developed in the authors' reference [10] leads to

$$\frac{h\sigma}{k\psi} \quad \text{and} \quad \frac{p}{M}$$

which are the coordinates of Fig. 1

Using $q$ and $W$ in Fig. 2 instead of $q/A$ and $W/A$ spreads data for various test-sample sizes along the line, even though pressure is the same. Note five-decade scales in Fig. 2 vs. three-decade scales in Fig. 1.

Note also that the effect of doing the dimensional analysis with $q$ and $W$ is not only to remove $A$ from each denominator, but also to put $\sigma$ in the denominator of $C/\sigma k$ instead of the numerator $h\sigma/k\psi$ where the analysis of reference [10] suggests it should properly be.

We suggest the appropriate way to interpret contact-conductance data is with the parameters of Fig. 1 and not those of Fig. 2.

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## E. Fried[5]

The authors of this paper are to be commended for having undertaken the tedious task of evaluating, reducing, and presenting data of many investigators for the purpose of developing a general correlation for thermal contacts in a vacuum. Having attempted a number of such empirical correlations, this discusser is aware of the difficulty inherent in such a task, especially if the objective of such work is to provide results in a form convenient for design engineers.

While Holm's original work on electric contacts [36] has provided the basis of a significant portion of the existing thermal-contact literature, the reason for use of reference [12] in preference to Tien [9] or Cooper et al. [10] to obtain the authors' dimensionless conductance $C^*$ and load $W^*$ would be of interest to many workers in this field. Holm's objection to the use of nominal areas could readily be accommodated by converting the experimental data to conductance $C$ and load $W$ by multiplying the appropriate terms by the nominal area before attempting the correlation. This was, in fact, done when this discusser supplied Holm with experimental data, when Holm prepared reference [12]. Having attempted to use it, this discusser agrees with the present authors that Holm's correlation [12] is inconclusive and not suitable for design applications.

This leads to the question of whether a suitable general correlation of thermal-contact conductance exists or can be developed. The present authors have been able to correlate data for aluminum joints and data for stainless steel joints, where the slopes of the correlation are in good agreement but do not coincide. Correlations similar to these, but using Holm's [36] $a$-spots ($\bar{a}$ = radius of contact spots) as the characteristic dimension in the dimensionless conductance number, have been presented by Hsieh and Touloukian [31] and Malkov [34]. Hsieh in particular has utilized many of the experimental results cited in the present work and in [1] and categorized them according to ferrous and non-ferrous materials, wavy and nominally flat surfaces, and constant $\bar{a}$ or variable $\bar{a}$. Hsieh's correlations also show significant scatter, which indicates that there may be a missing parameter. Another general nondimensional correlation which deserves citation is that by Fletcher [37], who utilized the initial gap dimension as a characteristic dimension, in addition to a nondimensional temperature. This correlation had remarkably limited scatter and was the only correlation to consider interface temperature explicitly.

At this point, it is of interest to consider the common features of the present and all cited dimensionless correlations. They are, with the exception of Fletcher [37], of the form (Conductance Number) = Constant (Load Number)$^n$ but differ in the value of the constant and in the value of the exponent $n$. Table 3 shows typical forms of the nondimensional correlation terms used. From this, it can be seen that the terms other than the load $W$ serve to "normalize" the conductance $C$ for different materials, surface parameters, and physical properties. It is also evident, as the authors state in their discussion, that present correlations are either inadequate or that parts of the experimental data obtained and used for these correlations are inadequately defined.

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**Table 3**

| Reference | Conductance term | Load term | Load-term exponent (approx.) |
|---|---|---|---|
| Authors | $C/\sigma k$ | $W/\sigma^2 M$ | 0.73 |
| Tien [9] | $C\sigma/\psi Ak$ | $W/AM$ | 0.85 |
| Cooper et al. [10] | $C\sigma/\psi Ak$ | $W/AM$ | 0.99 |
| Hsieh et al. [31] | $C\bar{a}/Ak$ | $W/AM$ | 1.0 |
| Malkov [34] | $C\bar{a}/Ak$ | $W/AM$ | 0.66 |

Assumption: 3 × yield strength = $M$.


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## Authors' Closure

We regret that we were unable to discuss references [33] and [35] as they did not appear until after our manuscript had been submitted. We agree with Fletcher and Fried that inclusion of the mean interface temperature is likely to lead to a significant improvement in correlation, though it is a parameter which is not always readily available from published data. Fletcher's use of the elastic modulus in preference to the surface hardness is interesting. We are now ourselves of the opinion that surface contact in most engineering situations is elastic rather than plastic, and of course the elastic modulus is a much more well-defined parameter. We hope to repeat our present correlation with an appropriate modification.

The dimensionless groups suggested by Rohsenow and Mikic may well be more physically significant than ours, particularly for isotropic surfaces. However, the point of our paper was really to provide a useful, if limited, correlation using published experimental data. Values of surface slopes have not hitherto been quoted in the heat transfer literature as the necessary measuring techniques have only recently become available and there are difficulties associated with their interpretation. It is not therefore very convenient at present to use $h\sigma/k\psi$ as a dimensionless conductance. A more fundamental objection to the suggestion is the difficulty of defining a unique value of $\psi$ for an anisotropic surface.