



BSI Standards Publication

Space Engineering — Thermal design handbook

Part 4: Conductive Heat Transfer

National foreword

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European Foreword

This document (CEN/CLC/TR 17603-31-04:2021) has been prepared by Technical Committee CEN/CLC/JTC 5 “Space”, the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-31.

This Technical report (TR 17603-31-04:2021) originates from ECSS-E-HB-31-01 Part 4A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

1

Scope

This Part 4 of the spacecraft thermal control and design data handbooks, provides information on calculating the conductive heat transfer rate for a variety of two and three-dimensional configurations.

Calculations for the conductance of the interface between two surfaces (joints) require special consideration and are included as a separate clause.

The Thermal design handbook is published in 16 Parts

TR 17603-31-01	Thermal design handbook – Part 1: View factors
TR 17603-31-02	Thermal design handbook – Part 2: Holes, Grooves and Cavities
TR 17603-31-03	Thermal design handbook – Part 3: Spacecraft Surface Temperature
TR 17603-31-04	Thermal design handbook – Part 4: Conductive Heat Transfer
TR 17603-31-05	Thermal design handbook – Part 5: Structural Materials: Metallic and Composite
TR 17603-31-06	Thermal design handbook – Part 6: Thermal Control Surfaces
TR 17603-31-07	Thermal design handbook – Part 7: Insulations
TR 17603-31-08	Thermal design handbook – Part 8: Heat Pipes
TR 17603-31-09	Thermal design handbook – Part 9: Radiators
TR 17603-31-10	Thermal design handbook – Part 10: Phase – Change Capacitors
TR 17603-31-11	Thermal design handbook – Part 11: Electrical Heating
TR 17603-31-12	Thermal design handbook – Part 12: Louvers
TR 17603-31-13	Thermal design handbook – Part 13: Fluid Loops
TR 17603-31-14	Thermal design handbook – Part 14: Cryogenic Cooling
TR 17603-31-15	Thermal design handbook – Part 15: Existing Satellites
TR 17603-31-16	Thermal design handbook – Part 16: Thermal Protection System

2 References

EN Reference	Reference in text	Title
EN 16601-00-01	ECSS-S-ST-00-01	ECSS System - Glossary of terms

All other references made to publications in this Part are listed, alphabetically, in the **Bibliography**.

Terms, definitions and symbols

3.1 Terms and definitions

For the purpose of this Standard, the terms and definitions given in ECSS-S-ST-00-01 apply.

3.2 Abbreviated terms

The following abbreviated terms are defined and used within this Standard.

FD	flatness deviation, [m]
RD	roughness deviation, [m]
TWL	total weight loss, percent
VCM	volatile condensable materials, percent by weight

Other symbols, mainly used to define the geometry of the configuration, are introduced when required.

3.3 Symbols

<i>A</i>	cross-sectional area normal to temperature gradient, [m ²]
<i>E</i>	modulus of elasticity, [Pa]
<i>L</i>	length normal to the plane of the figure in two-dimensional configurations, [m]
<i>M</i>	surface hardness, [Pa]
<i>P</i>	applied compressive load, also called contact pressure, [Pa]
<i>Q</i>	heat transfer rate, [W]

S	langmuir conductive shape factor, [m]
T	temperature, [K]
T_m	arithmetic mean temperature, [K]
b	Clause 2: radius of the specimen, [m]
d	surface parameter in Fletcher & Gyorog correlation, [m]
h_c	thermal joint conductance, [W.m ⁻² .K ⁻¹]
h_f	interstitial contribution to thermal joint conductance, [W.m ⁻² .K ⁻¹]
h_r	radiative contribution to thermal joint conductance, [W.m ⁻² .K ⁻¹]
h_s	solid contribution to thermal joint conductance, [W.m ⁻² .K ⁻¹]
k	thermal conductivity, [W.m ⁻¹ .K ⁻¹]
k_m	mean thermal conductivity, [W.m ⁻¹ .K ⁻¹]. $k_m = 2k_1k_2/(k_1+k_2)$
l	heat path length, [m]
p	ambient pressure, [Pa]
r	filter rating, [m]
t	thickness, [m]
ΔT	interfacial temperature drop, [K]
ϕ	porosity
β	coefficient of linear thermal expansion, [K ⁻¹]
δ_0	gap thickness parameter in Fletcher & Gyorog correlation, [m]
ρ	density, [kg.m ⁻³]
σ	rms surface roughness, [m]

Conductive shape factors

4.1 General

The conductive heat transfer rate through fairly complicated two-or-three dimensional configurations can be estimated on the basis of the so-called conductive shape factor, S .

In order to introduce the concept of conductive shape factor it is customary to start with the expression giving the one-dimensional conductive heat transfer rate, Q , between two parallel planar surfaces, 1 and 2, of cross-sectional area, A . Assuming that the thermal conductance k , of the space between the planes is constant, Fourier's law yields the following equation:

$$Q = k(A/l)(T_2 - T_1) = kS(T_2 - T_1),$$

l being the distance between the planes.

The factor S , known as Langmuir conductive shape factor, is, in this case, the ratio of the cross-sectional area, A , to the heat path length, l .

When two-or-three dimensional configurations are involved, the temperature field can be calculated by use of one of the methods available to solve Laplace differential equations. In many instances, however, only the overall heat transfer rate between arbitrary surfaces, 1 and 2, is required, and the above expression giving Q can be used, provided that S represents the ratio of the average cross-sectional area to the average heat path length. although the mathematical problem must be solved in full, in order to calculate S , the resulting values of S can be displayed in a very compact and useful way, as it is shown in this clause.

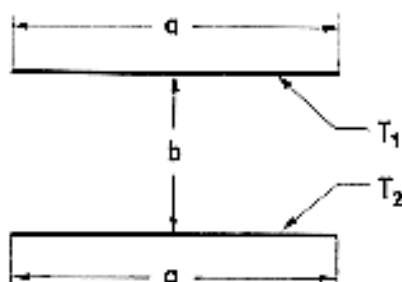
It should be mentioned that for two-dimensional configurations, that is to say, configurations which do not depend on the coordinate normal to the plane of the figure, the heat transfer rate is to be understood as that corresponding to the unit length normal to the mentioned plane. In order to keep unchanged the physical dimensions of S , the conductive shape factor for two-dimensional configurations is defined as S/L , which is a dimensionless magnitude.

4.2 Planar-planar surfaces

4.2.1 Two-dimensional configurations

4.2.1.1 Strips of equal width

Two parallel strips of equal width.



Formula:

$$S/L = a/b$$

Comments:

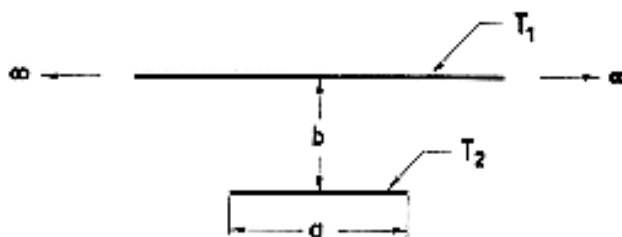
The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

References: Andrews (1955) [3], Sunderland & Johnson (1964) [46].

4.2.1.2 Strips of unequal width

Finite width strip and infinite parallel plane.



Formula:

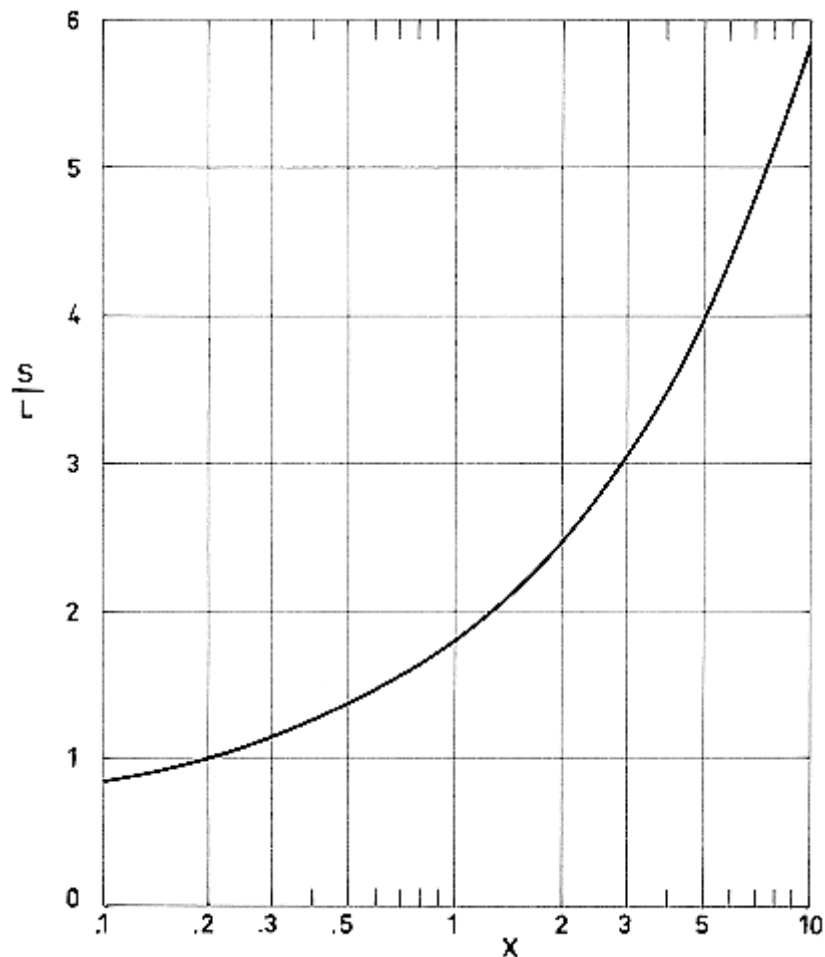
$$\frac{S}{L} = 1,45 \left[\ln \left(1 + \frac{1}{X} \right) \right]^{-0,59} \quad [4-1]$$

Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-1.



Note: non-si units are used in this figure

Figure 4-1: Values of the conductive shape factor per unit length, S/L , vs. the dimensionless width of the strip, X . Calculated by the compiler.

Reference: Andrews (1955) [3].

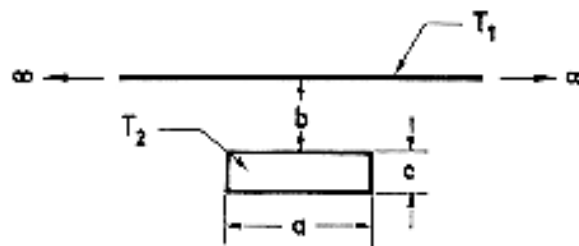
4.3 Planar surface-cylindrical surface

4.3.1 Two-dimensional configurations

4.3.1.1 Plane and cylinder of rectangular cross section

Plane and cylinder of rectangular cross section. The plane is parallel to the base of the rectangle.

The cylinder is assumed to be infinitely conductive.



Formula:

$$\frac{S}{L} = 1,685 \left[\ln \left(1 + \frac{1}{X} \right) \right]^{-0,59} \left[\frac{1}{Y} \right]^{-0,078} \quad [4-2]$$

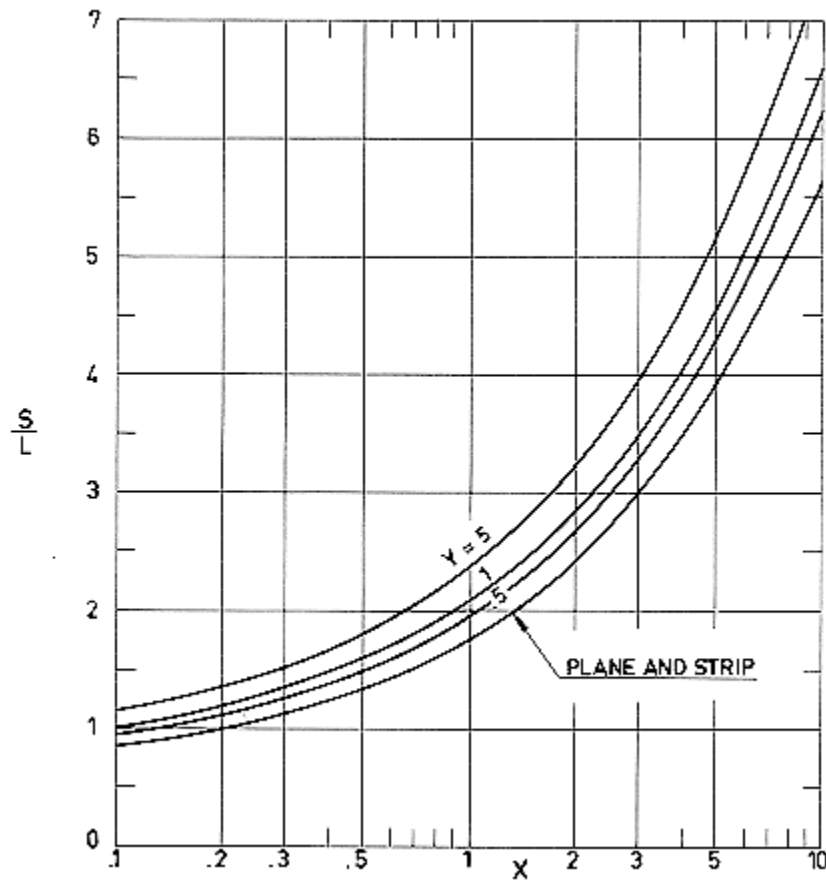
Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The above expression has been obtained by means of the electric analogy, using a conductive paper of finite dimensions (Andrews (1955) [3]). Since it is not stated in the reference how the point at infinity has been taken into account, results for small values of Y , which is presumably correspond to large values of b , are doubtful. In Figure 4-2 the finite strip case (see clause 4.2.1.2) has been taken to bound below the recommended values.

The results are given in Figure 4-2.



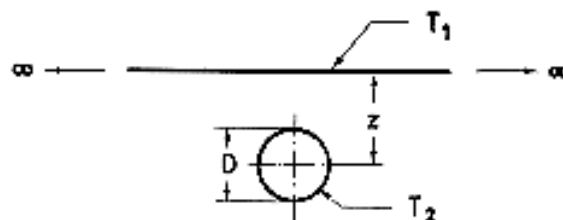
Note: non-si units are used in this figure

Figure 4-2: Values of the conductive shape factor per unit length, S/L , vs. X for different values of Y . Calculated by the compiler.

References: Andrews (1955) [3], Sunderland & Johnson (1964) [46].

4.3.1.2 Plane and circular cylinder

Plane and circular cylinder whose axis is parallel to the plane.



The cylinder is assumed to be infinitely conductive.

$$Z = D/z$$

Formula:

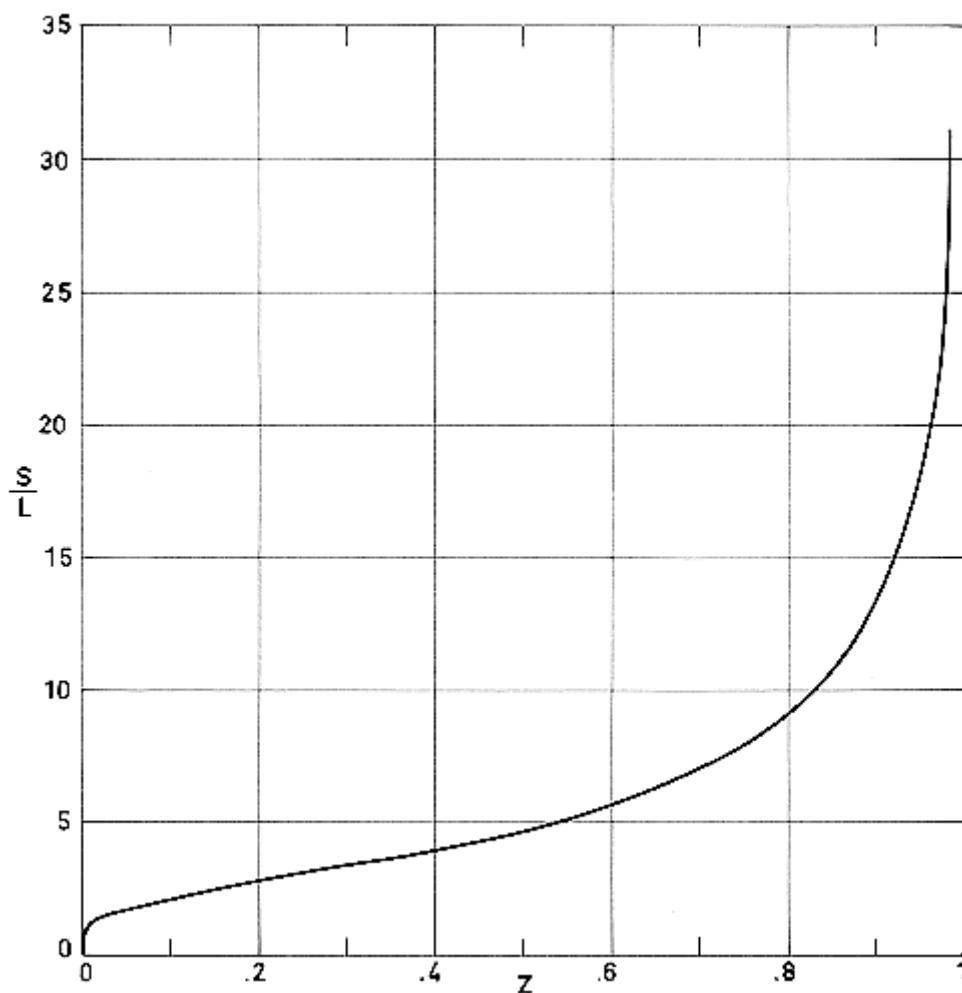
$$\frac{S}{L} = \frac{2\pi}{\cosh^{-1} \frac{2}{Z}} \quad [4-3]$$

Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-3.



Note: non-si units are used in this figure

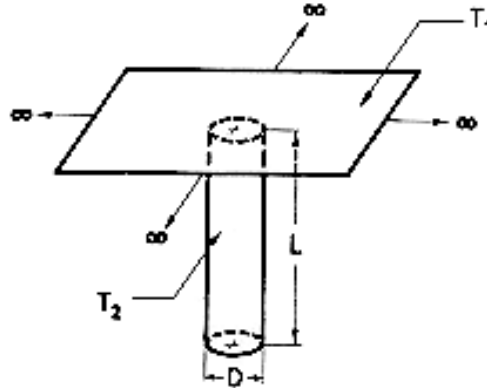
Figure 4-3: Values of the conductive shape factor per unit length, S/L , vs. dimensionless diameter of the cylinder cross section. Calculated by the compiler.

References: Sunderland & Johnson (1964) [46], Kutateladze & Borishanskii (1966) [28].

4.3.2 Axisymmetrical configuration

4.3.2.1 Plane and circular cylinder

Plane and circular cylinder of finite length with its base on the plane.



The cylinder is assumed to be infinitely conductive.

$$D \ll L$$

Formulae:

$$\frac{S}{L} = \frac{2\pi}{\ln \frac{4L}{D}} \quad (a) \quad [4-4]$$

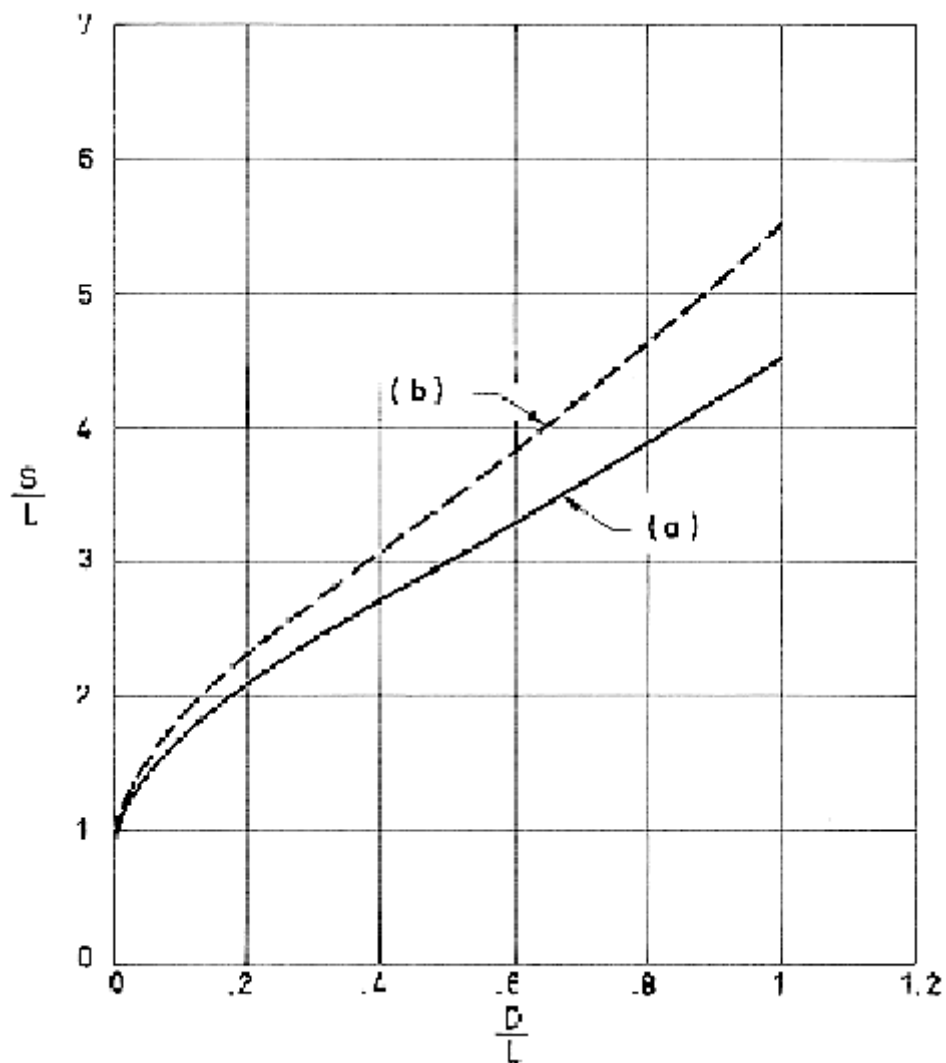
$$\frac{S}{L} = \frac{2\pi}{\ln \frac{4L}{D}} - \frac{2\pi(2\ln \sqrt{2} - 1)}{\left(\ln \frac{4L}{D}\right)^2} \quad (b) \quad [4-5]$$

Comments:

To obtain expression (a) the end effects corresponding to the free end of the cylinder have been neglected, so that this expression is only valid when the cylinder is slender enough.

Expression (b), which includes the second asymptotic term of the three-dimensional solution, has been obtained by the compiler.

The results are given in Figure 4-4.



Note: non-si units are used in this figure

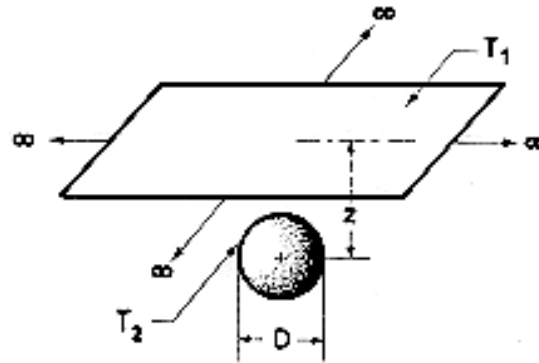
Figure 4-4: Values of the dimensionless conductive shape factor, S/L , vs. cylinder diameter to length ratio, D/L . Calculated by the compiler.

References: Sunderland & Johnson (1964) [46], Kutateladze & Borishanskii (1966) [28]; Parker, Boggs & Blick (1969) [36].

4.4 Planar surface-spherical surface

4.4.1 Plane and sphere

Plane and sphere.



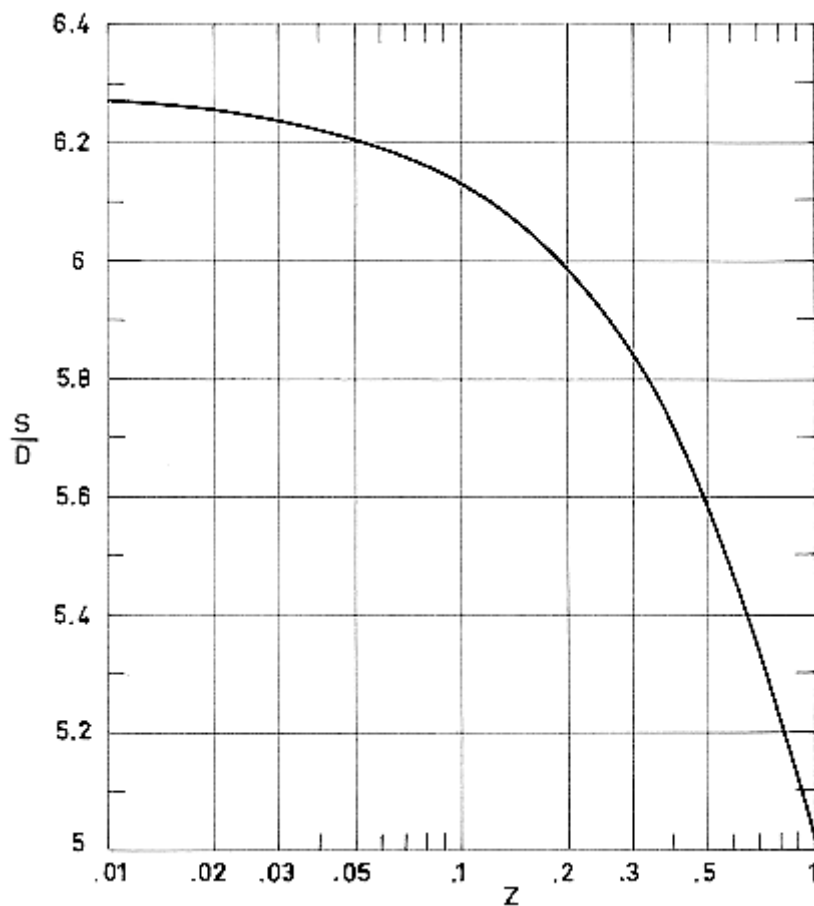
The sphere is assumed to be infinitely conductive.

$$Z = D/z$$

Formula:

$$\frac{S}{D} = \frac{2\pi}{1 + \frac{Z}{4}} \quad [4-6]$$

The results are given in Figure 4-5.



Note: non-si units are used in this figure

Figure 4-5: Values of the dimensionless conductive shape factor, S/D , vs. the dimensionless diameter of the sphere, Z . Calculated by the compiler.

References: Andrews (1955) [3], Sunderland & Johnson (1964) [46], Kutateladze & Borishanskii (1966) [28]; Parker, Boggs & Blich (1969) [36].

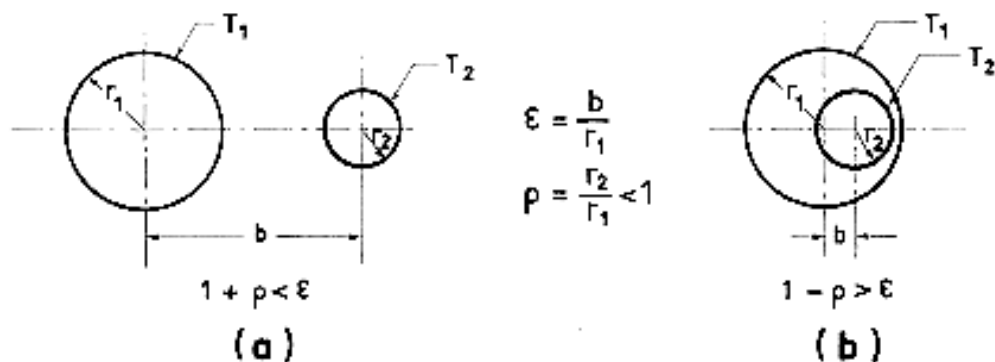
4.5 Cylindrical-cylindrical surfaces

4.5.1 Two-dimensional configurations

4.5.1.1 Circular cylinders

Parallel circular cylinders.

Both cylinders are assumed to be infinitely conductive.



Formula:

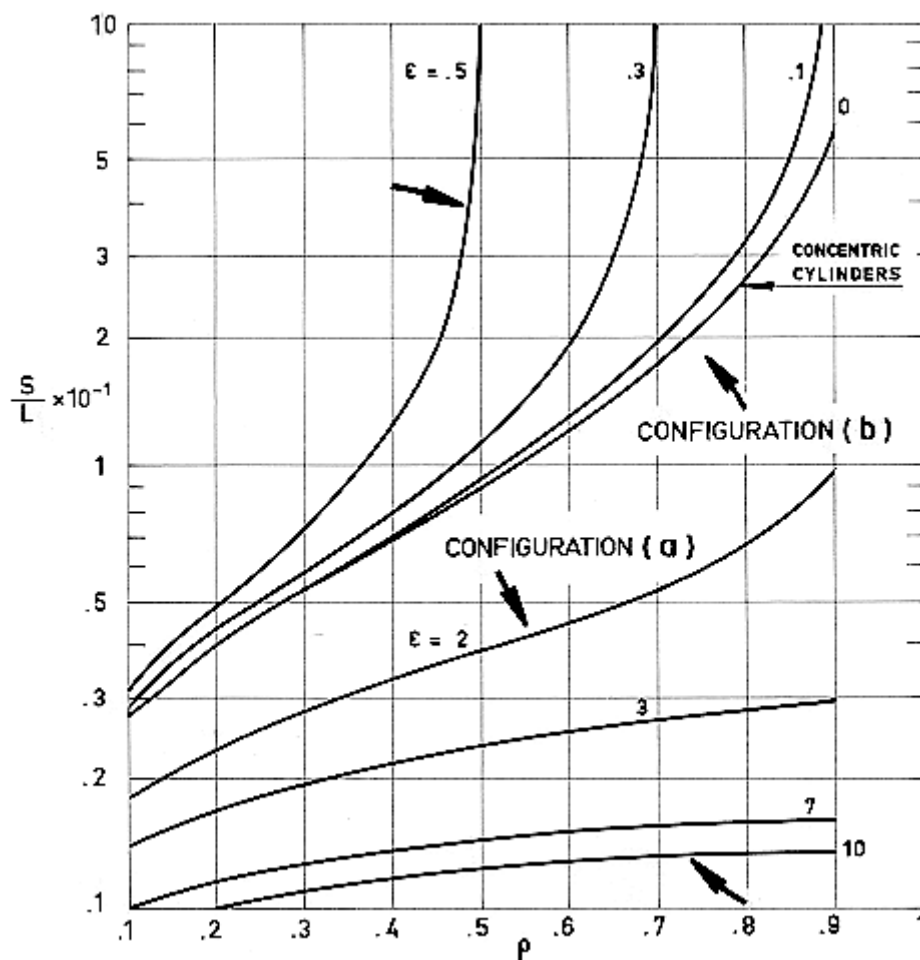
$$\frac{S}{L} = \frac{2\pi}{\cosh^{-1} \left[\frac{1 + \rho^2 - s^2}{2\rho} \right]} \quad [4-7]$$

Comments:

Both configurations are two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-6.



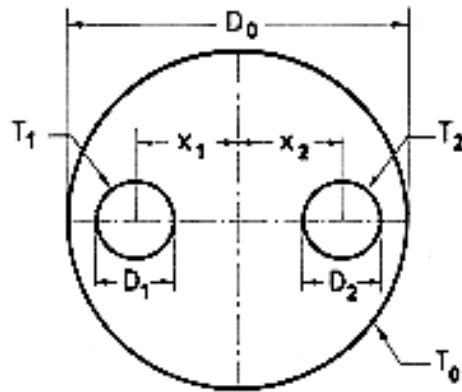
Note: non-si units are used in this figure

Figure 4-6: Values of the conductive shape factor per unit length, S/L , vs. radius ratio, ρ , for different values of the dimensionless distance between cylinder axes, ϵ . Calculated by the compiler.

References: Andrews (1955) [3], Sunderland & Johnson (1964) [46]; Parker, Boggs & Blick (1969) [36].

4.5.1.2 Circular rods with holes

Circular rod with two circular holes.



$$X_i = x_i/D_0$$

$$d_i = D_i/D_0$$

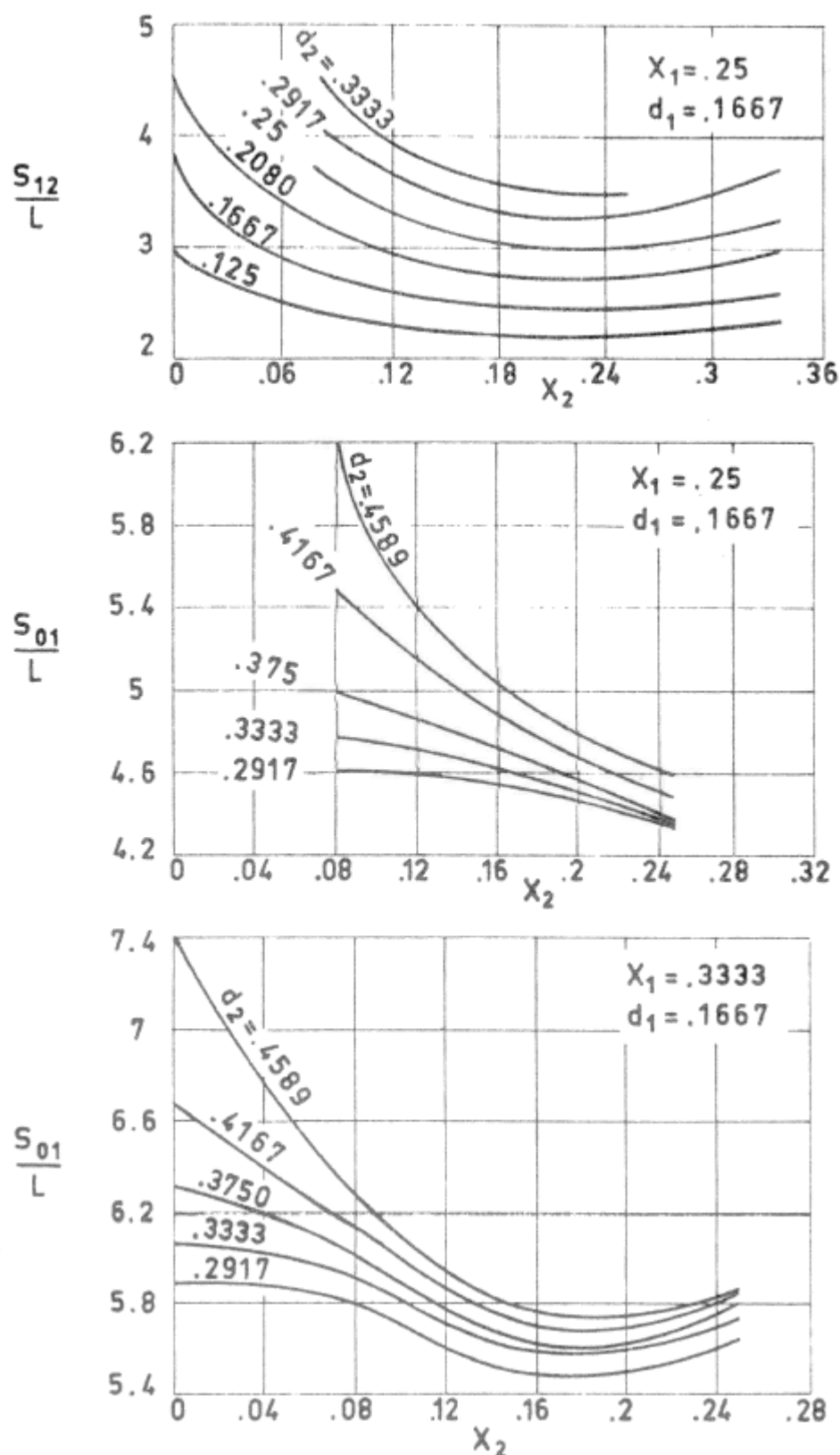
The results presented have been obtained by using an electrical analogue method.

Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-7.

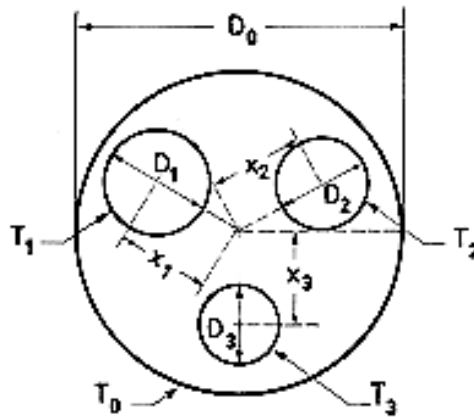


Note: non-si units are used in this figure

Figure 4-7: Values of the dimensionless conductive shape factors per unit length, S_{ij}/L , vs. the eccentricity of one of the holes X_2 , for different values of the relevant geometrical parameters. From Faulkner & Andrews (1955) [13].

Reference: Faulkner & Andrews (1955) [13].

Circular rod with three circular holes.



$$X_i = x_i/D_0$$

$$d_i = D_i/D_0$$

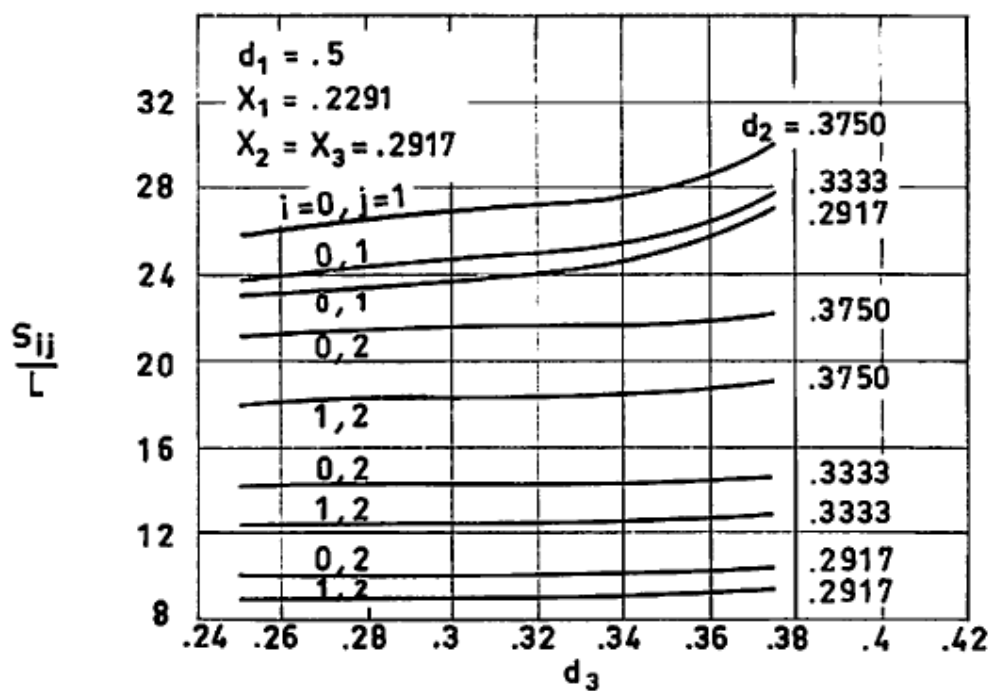
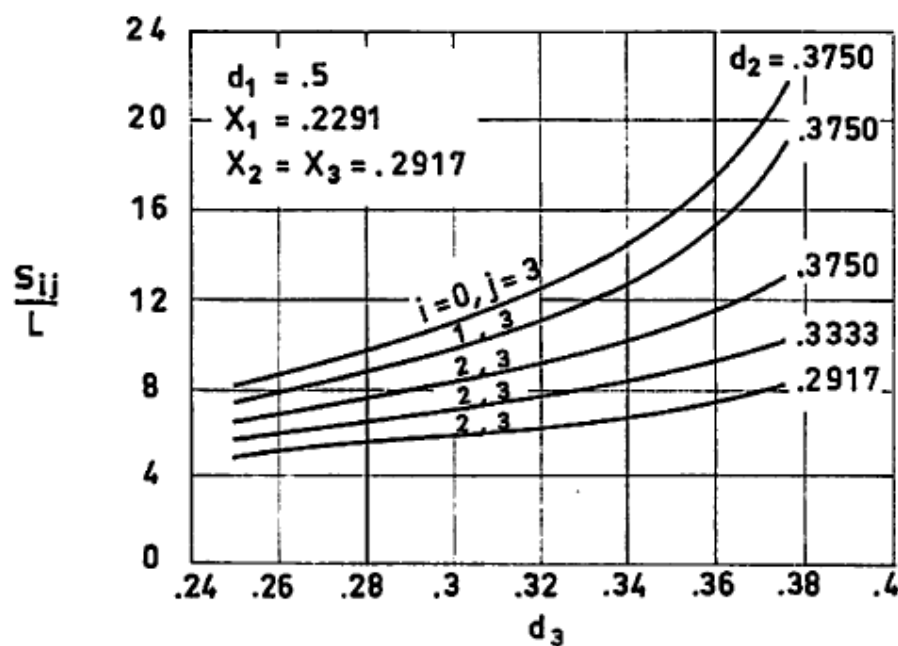
The results presented have been obtained by using an electrical analogue method.

Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-8.

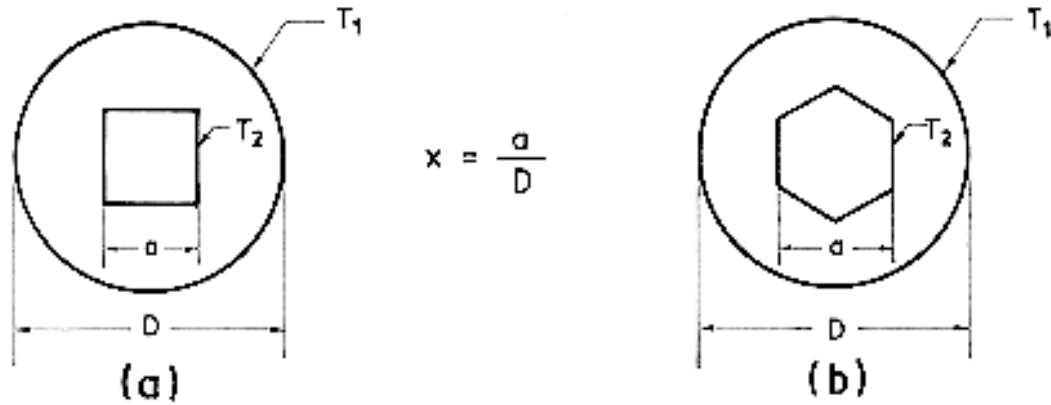


Note: non-si units are used in this figure

Figure 4-8: Values of the conductive shape factors per unit length, S_{ij}/L , vs. the diameter ratio d_3 , for different values of the relevant geometric parameters. From Faulkner & Andrews (1955) [13].

Reference: Faulkner & Andrews (1955) [13].

Circular rod with square or hexagonal concentric holes.



Formulae:

$$(a) \quad \frac{S}{L} = \frac{6,533}{\ln \frac{1}{x} - 0,15921} \quad [4-8]$$

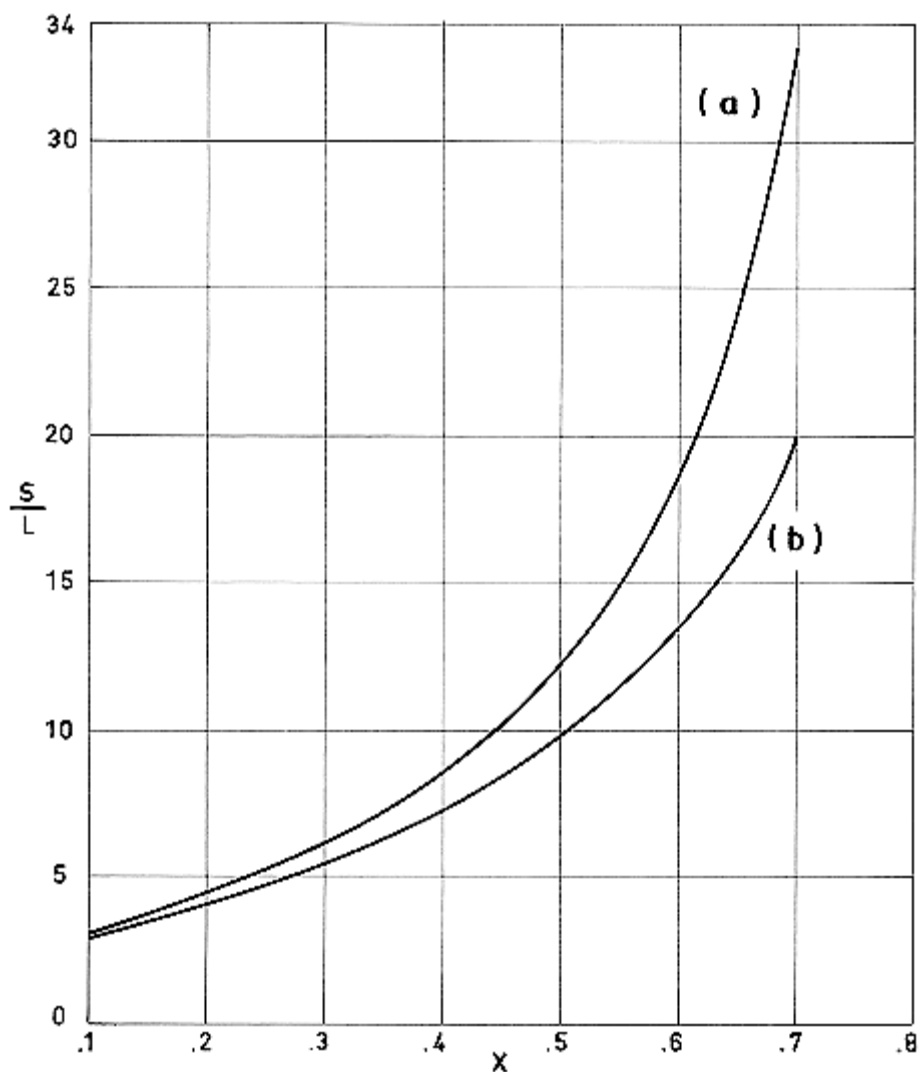
$$(b) \quad \frac{S}{L} = \frac{6,46}{\ln \frac{1}{x} - 0,03147} \quad [4-9]$$

Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-9.



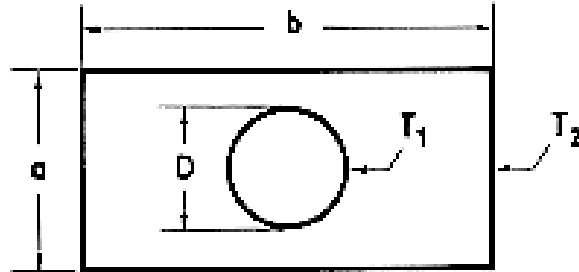
Note: non-si units are used in this figure

Figure 4-9: Values of the conductive shape factor per unit length, S/L , vs. the dimensionless characteristic length of the holes, X . Calculated by the compiler.

Reference: Ramachandra Murthy & Ramachandran (1967) [40].

4.5.1.3 Rectangular bars with holes

Rectangular bar with a concentric circular hole:



$$X = D/a$$

$$Y = b/a$$

Formula:

$$\frac{S}{L} = \frac{2\pi}{\ln \frac{4}{\pi X} - 2k} \quad [4-10]$$

where k is a coefficient which depends upon Y as indicated below

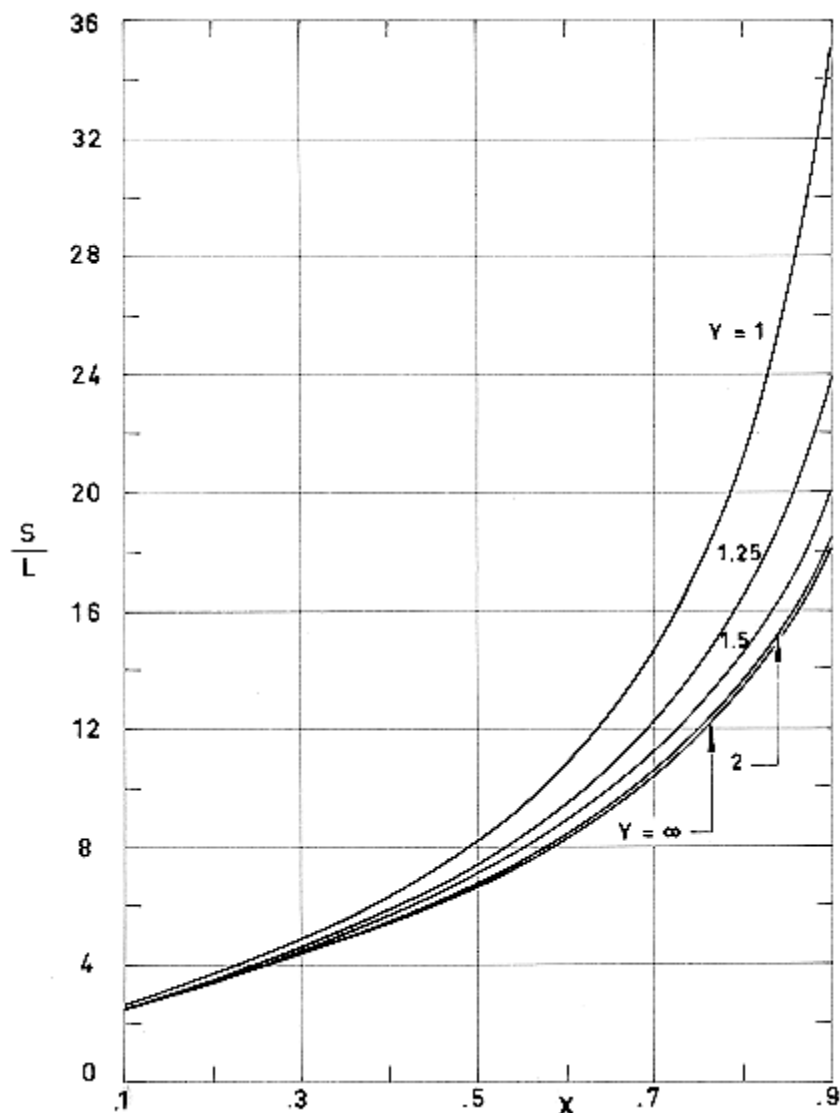
Y	k
1,00	0,08290
1,25	0,03963
1,50	0,01781
1,75	0,00816
2,00	0,00373
2,25	0,00170
2,50	0,00078
3,00	0,00016
4,00	$6,9748 \times 10^{-6}$
5,00	$3,0140 \times 10^{-7}$
10,00	$4,5422 \times 10^{-14}$
∞	0

Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-10.

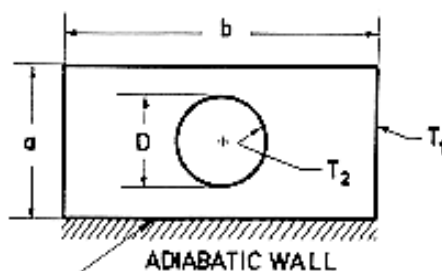


Note: non-si units are used in this figure

Figure 4-10: Values of the conductive shape factor per unit length, S/L , vs. the dimensionless diameter of the hole, X , for several values of the aspect ratio, Y , of the rectangular bar cross-section. Calculated by the compiler.

Reference: Sunderland & Johnson (1964) [46].

Rectangular bar having one adiabatic face and a concentric circular hole.



$$X = D/a$$

$$Y = b/a$$

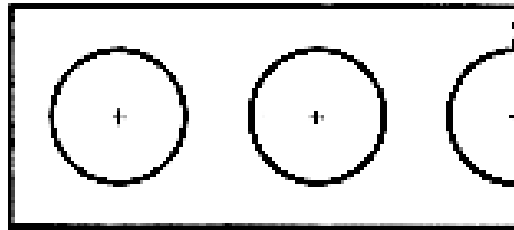
The results presented were obtained numerically.

Comments:

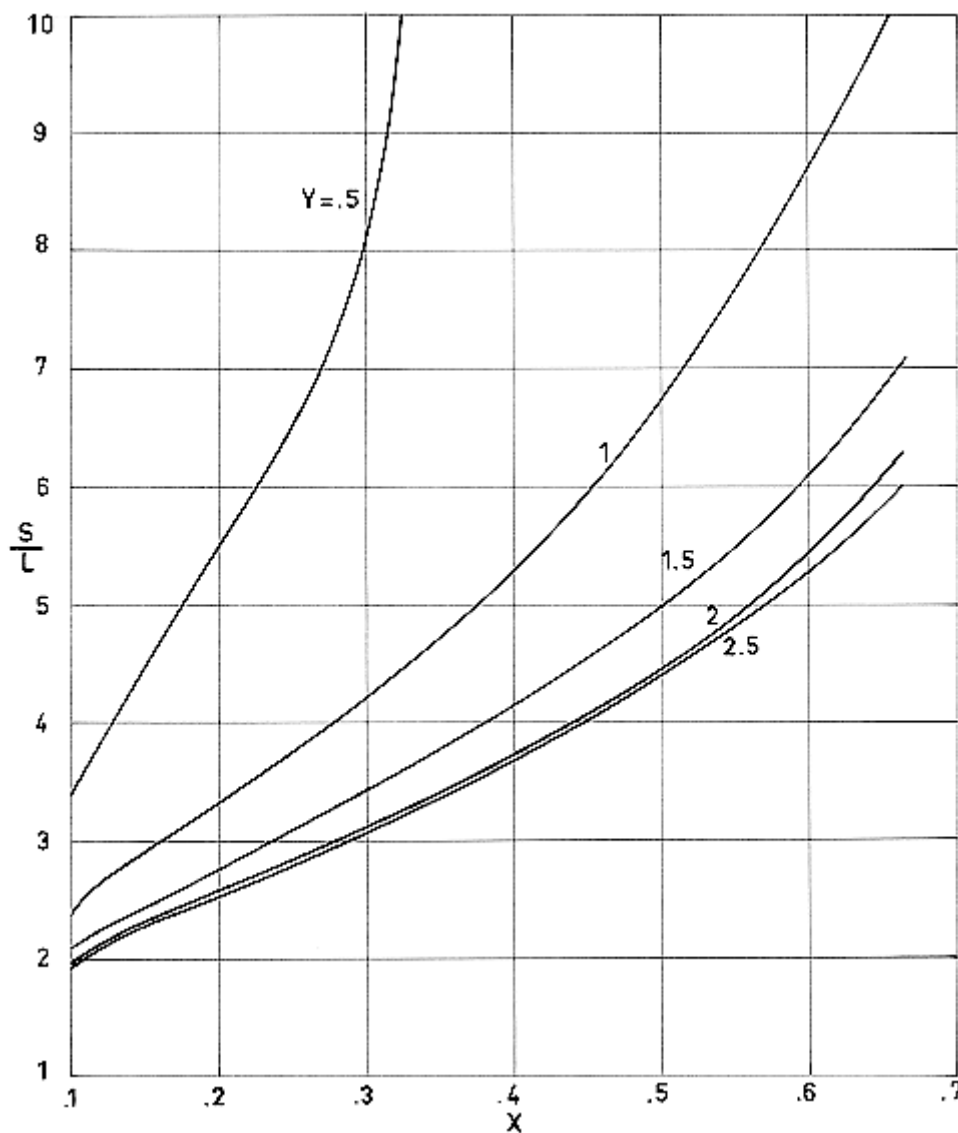
The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

These results can be used to study configurations similar to the one sketched below.



The results are given in Figure 4-11.

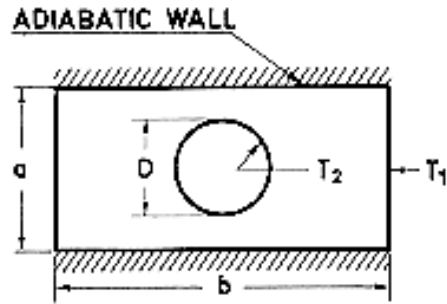


Note: non-si units are used in this figure

Figure 4-11: Values of the conductive shape factor per unit length, S/L , vs. the dimensionless diameter of the hole, X , for different values of the aspect ratio, Y , of the rectangular bar cross section. After Griggs, Pitts & Goyal (1973) [25].

Reference: Griggs, Pitts & Goyal (1973) [25].

Rectangular bar having two opposite adiabatic faces and a concentric circular hole.



$$X = D/a$$

$$Y = b/a$$

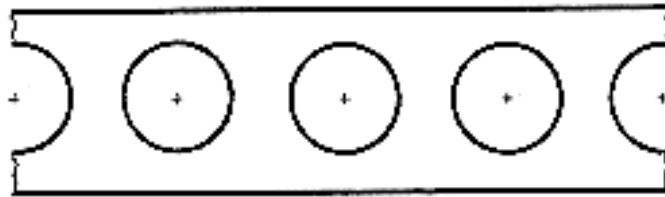
The results presented were obtained numerically.

Comments:

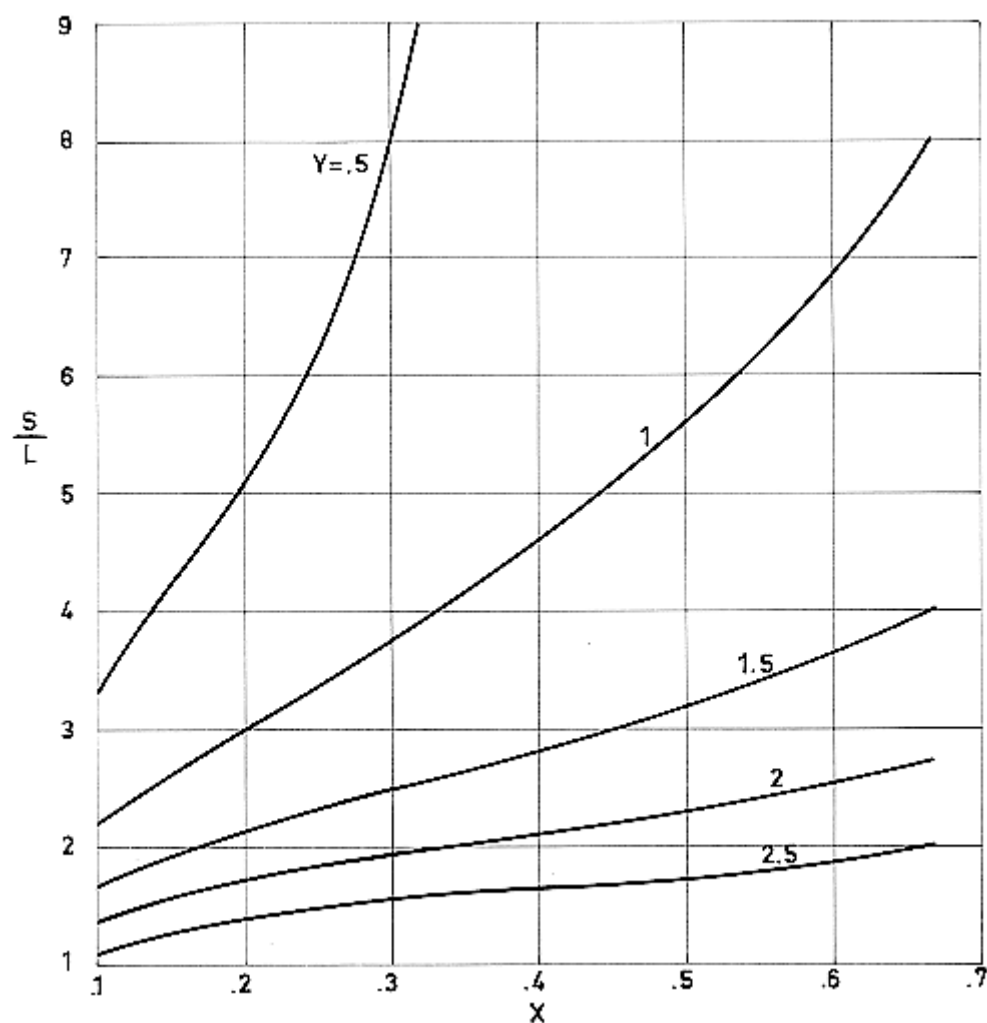
The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

These results can be used to study configurations similar to the one sketched below.



The results are given in Figure 4-12.



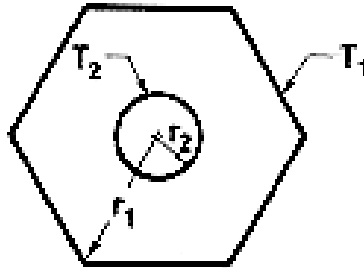
Note: non-si units are used in this figure

Figure 4-12: Values of the conductive shape factor per unit length, S/L , vs. the dimensionless diameter of the hole, X , for several values of the aspect ratio, Y , of the rectangular bar cross section. After Griggs, Pitts & Goyal (1973) [25].

Reference: Griggs, Pitts & Goyal (1973) [25].

4.5.1.4 Polygonal bars with holes

Cylinder with an n -sided regular cross section and a concentric circular hole:



$$\rho = r_2/r_1$$

Formula:

$$\frac{S}{L} = \frac{2\pi}{\ln\left(\frac{1}{\rho} - \frac{B}{2}\right)} \quad [4-11]$$

where B is a coefficient which depends upon n as indicated in the table below.

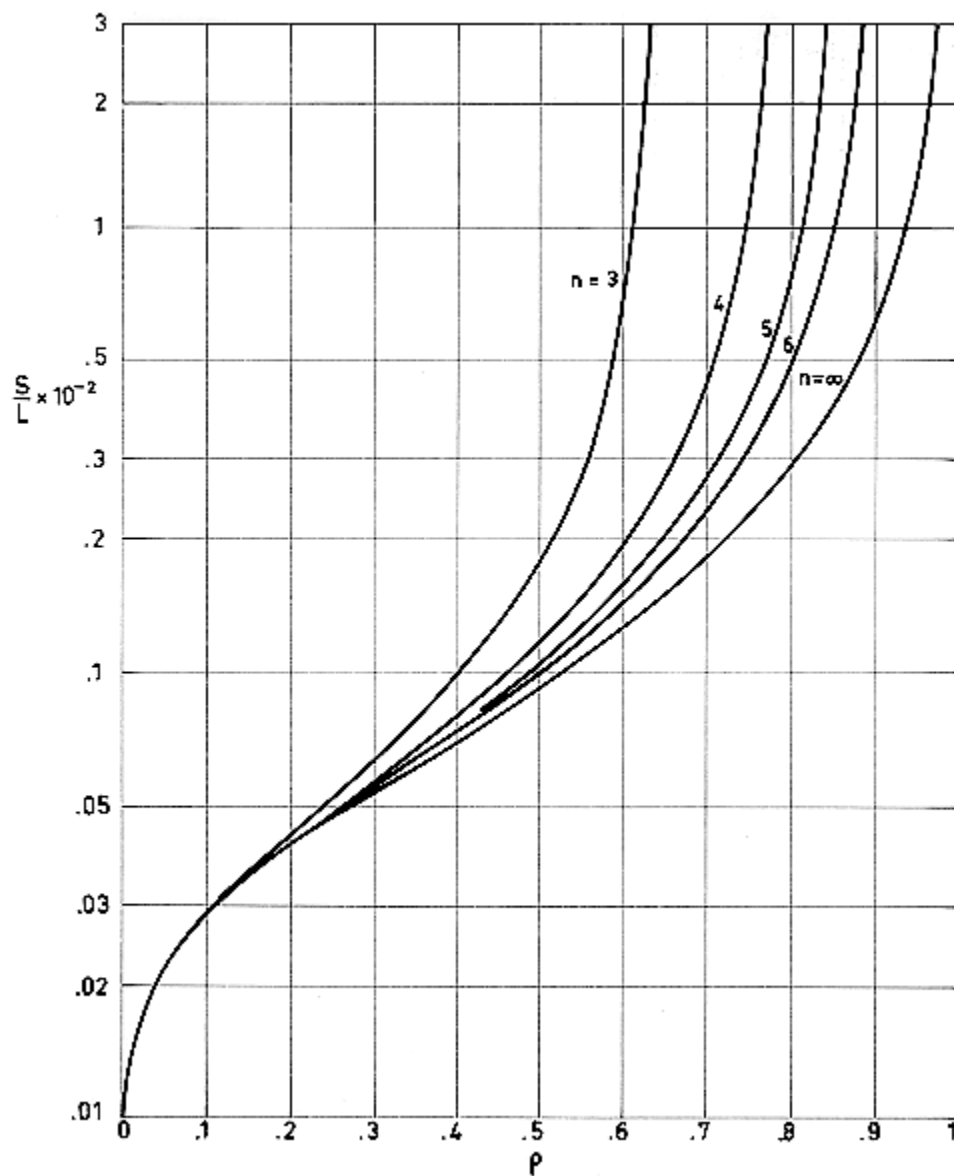
n	B
3	1,13916
4	0,54159
5	0,32131
6	0,21339
∞	0

Comments:

The configuration is two-dimensional.

S/L is the conductive shape factor per unit length normal to the plane of the figure.

The results are given in Figure 4-13.



Note: non-si units are used in this figure

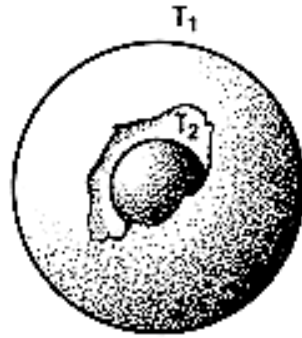
Figure 4-13: Values of the conductive shape factor per unit length, S/L , vs. the dimensionless hole radius, ρ , for several values of n . Calculated by the compiler.

Reference: Sunderland & Johnson (1964) [46].

4.6 Spherical-spherical surfaces

4.6.1 Two concentric spheres

Two concentric spheres.



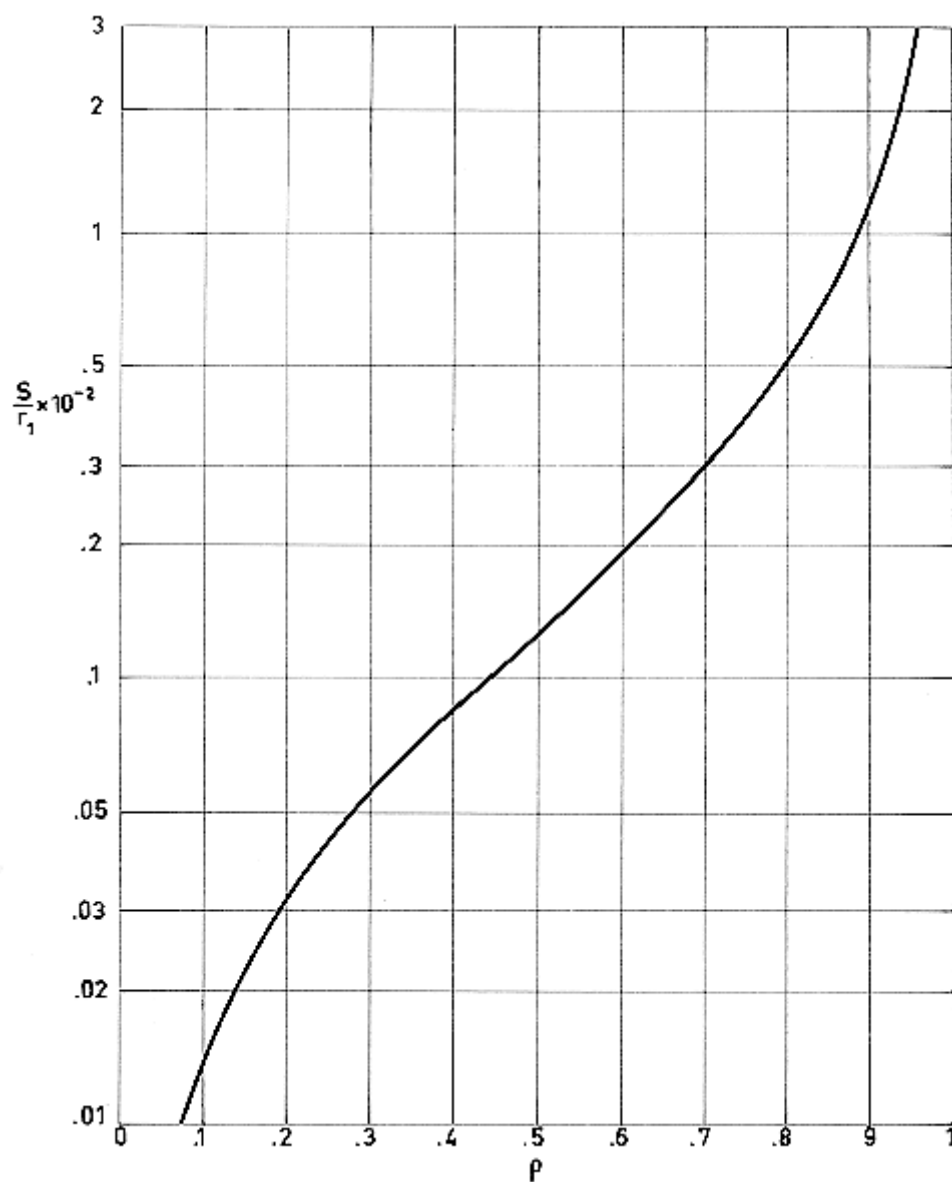
$$\rho = r_2/r_1$$

where r_1 and r_2 are the radii of the outer and inner sphere, respectively.

Formula:

$$\frac{S}{r_1} = \frac{4\pi}{\frac{1}{\rho} - 1} \quad [4-12]$$

The results are given in Figure 4-14.



Note: non-si units are used in this figure

Figure 4-14: Values of the dimensionless conductive shape factor, S/r_1 , vs. radius ratio, ρ . Calculated by the compiler.

Reference: Parker, Boggs & Blick (1969) [36].

Thermal joint conductance

5.1 General

The interface existing between two surfaces in contact introduces a resistance to heat transfer between the materials making up the contact. The thermal conductance, h_c , between these surfaces is given by:

$$h_c = (Q/A)/(\Delta T),$$

where:

Q/A , Heat flux across the interface. [W.m^{-2}].

ΔT , Interfacial temperature drop, estimated as in Figure 5-1. [K].

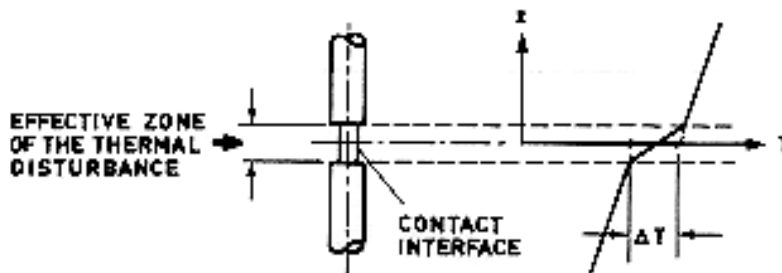


Figure 5-1: Estimation of the temperature drop at the interface.

The thermal conductance, h_c , which depends on the actual contact area and on the physical properties of the mating materials, can be split into three contributions, namely: the radiative, h_r , interstitial, h_f , and solid, h_s , contributions

$$h_c = h_r + h_f + h_s.$$

The radiative contribution, h_r , can be neglected for temperatures below 900 K, as shown by Fenech & Rohsenow (1959) [15] and by Clausen & Chao (1965) [7].

Concerning h_f , no generally valid method has been developed up to the moment to predict its contribution. The problem has been considered, among others, by Cetinkale & Fishended (1951) [6], Laming (1961) [29], Fenech & Rohsenow (1963) [14], and Henry & Fenech (1964) [27].

The contribution, h_s , of the solid contacting materials has been calculated, in the case of very simple geometrical configurations, by Roess (1949) [41], Laming (1961) [29], Clausen & Chao (1965) [7], Fenech & Rohsenow (1963) [15], and Henry & Fenech (1964) [27]. However, the direct application of these data is impeded by the impossibility of correctly defining the geometrical characteristics of the contact area under practical conditions.

Because of the difficulties which have been mentioned, the use of empirical correlations based on directly measurable parameters should be recommended. These correlations, which are based on dimensional considerations for the selection of the relevant dimensionless groups of parameters, include together the contributions of h_r , h_f , and h_s .

Unfortunately, only correlations for bare contacting metals have reached widespread use, thence, when information on the contact conductance between similar metals separated by a suitable spacer material is required, one must resort to the use of experimental data on systems which resemble as much as possible the configuration which is expected to be used in the real case.

Recently Al-Astrabadi et al. (1977) [2] correlated data on thermal contact conductance's for stacks of thin layers in high vacuum. Data from different sources, for both bare metals and plastic layers, correlate fairly in terms of appropriate dimensionless parameters.

5.1.1 Empirical correlations

5.1.1.1 Fletcher & Gyorog correlation

The following expression to predict the thermal conductance of contacting metal surfaces in a vacuum has been suggested by Fletcher & Gyorog (1970) [17].

$$h_c = \frac{km}{\delta_o} \left[5,22 \times 10^{-6} \frac{\delta_o}{b} + 0,036 \frac{P}{E} \beta T_m \right]^{0,56} \exp \left[170 \frac{\frac{P}{E} \beta T_m}{\delta_o / b} \right] \quad [5-1]$$

where:

E , Modulus of Elasticity. [Pa].

P , Applied Compressive Load. [Pa].

T_m , Mean Temperature. [K].

b , Specimen Radius. [m].

h_c , Thermal Contact Conductance. [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$].

km , Mean Thermal Conductivity. [$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$].

$km = 2k_1k_2/(k_1+k_2)$. k_1 and k_2 are thermal conductivities of the mating materials.

β , Coefficient of Linear Thermal Expansion. [K^{-1}].

δ_o , Gap Thickness Parameter. [m].

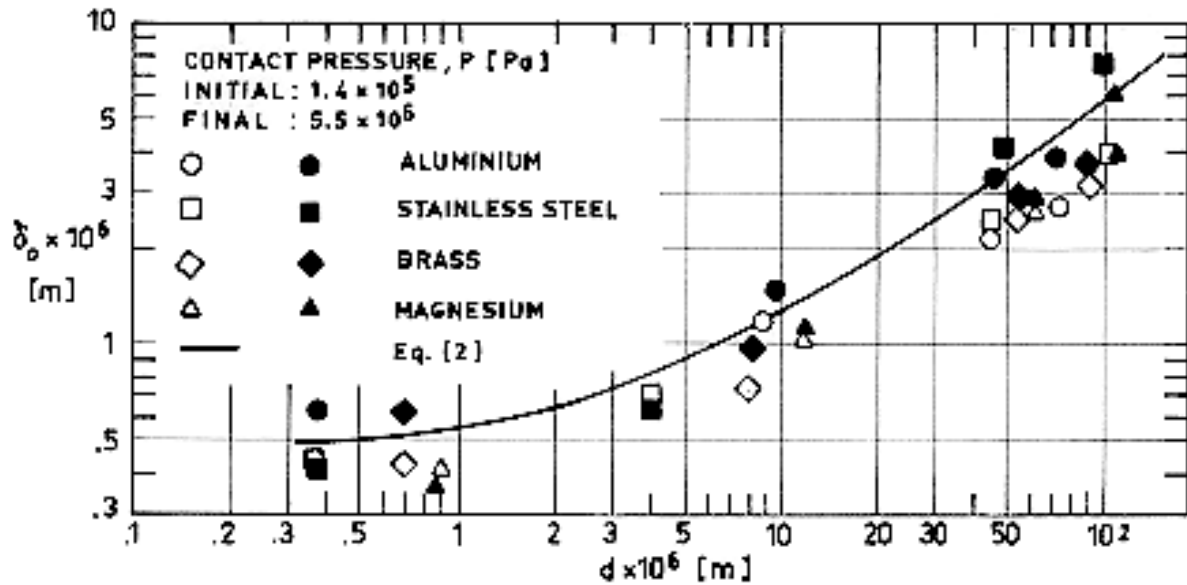
$$\delta_o = 0,519 \times 10^{-6} + 0,806 \times 10^{-1} d - 0,622 \times 10^3 d^2 + 0,211 \times 10^7 d^3 \quad [5-2]$$

$d = (FD + 2RD)_{\text{rough surface}}^{-1/2} (FD + 2RD)_{\text{smooth surface}}$. [m].

FD, Flatness Deviation. [m].

RD, Roughness Deviation. [m].

The gap thickness parameter, δ is represented as a function of d in Figure 5-2. Experimental data from different sources are included in this figure.



Note: non-si units are used in this figure

Figure 5-2: Variation of gap thickness parameter, δ_o , with contact surface parameter, d . After Fletcher & Gyrog (1970) [17].

The thermal conductance, h_c , is plotted vs. the load pressure, P , in Figure 5-3. Again the empirical correlation is compared with data from several sources. A mean error of 24% is reported by the authors.

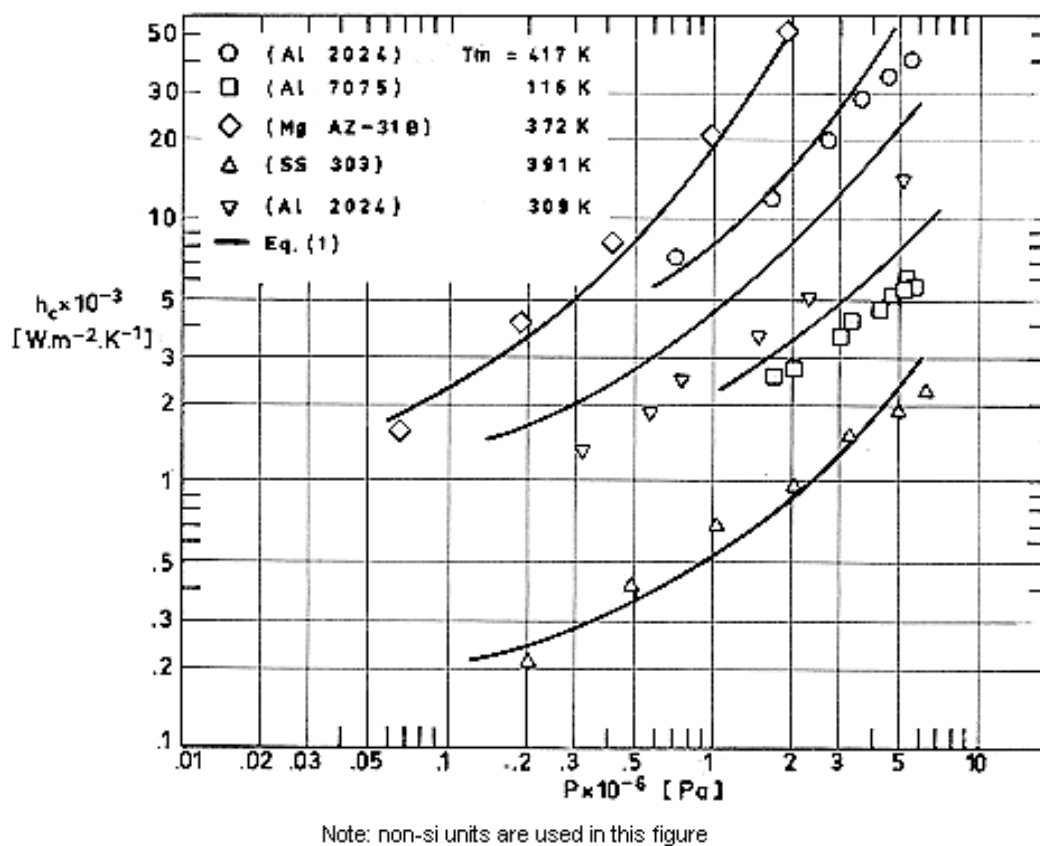


Figure 5-3: Variation of contact conductance with apparent interface pressure.
After Fletcher & Gyrog (1970) [17].