Thermal contact conductance

**Author:**
Villanueva, Eliseo P.

**Publication Date:**
1997

**DOI:**
https://doi.org/10.26190/unswworks/4697

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THERMAL CONTACT CONDUCTANCE

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

by

Eliseo P. Villanueva

School of Mechanical and Manufacturing Engineering
University of New South Wales
November, 1997
ABSTRACT

Theoretical and experimental works on thermal rectification of similar and dissimilar materials, effect of metallic foils on thermal contact conductance and directional effect on gas gap conductance are presented. A theoretical model of the contact of two nominally flat surfaces and a computer program based on the model were developed. It is modelled as contact of asperities with spherically shaped caps. The effect of oxide layer formed on the contacting surfaces was considered in the model. The model is designed to calculate the thermal contact conductance and predict the occurrence of thermal rectification.

An apparatus was designed and fabricated for the experimental part of the work. It has unique features that are considered improvements of the conventional types.

A number of experiments were performed in order to validate the model. The specimens were made of stainless steel, NILO 36, and aluminium. The experimental results agreed with the model by ±15% in the moderate to high contact pressure range. Both the theoretical and experimental results indicate positive thermal rectification if the heat flows from the surface of smaller radius of asperity to that of larger radius.

The experimental results on the effect of metallic inserts using gold and aluminium foils when compared with a bare joint showed a considerable increase in thermal conductance. The results using thick aluminium foils agreed with the model for thick interstitial material by ±5% in the low to moderate contact pressure range.

The existing theory for gas gap conductance is slightly modified by considering the effect of surface distortion. The results using air, argon, helium and nitrogen gases showed that gas gap conductance is a strong function of the gas thermal conductivity.

Availability of the parameters such as accommodation coefficient and correlations regarding effective gap width are necessary for the accurate prediction of the directional effect.
ACKNOWLEDGEMENTS

I would like to express my sincere appreciation and gratitude to the following:

the Australian Agency for International Development and the Mindanao State University – Iligan Institute of Technology (Philippines) for the scholarship grant and financial support;

Dr. Chakravarti V. Madhusudana, my supervisor, for introducing to me the concept about the problem on thermal contact conductance, and further, giving support by assisting in all aspects that were required in the work;

Assoc. Prof. Masud Behnia, the co-supervisor, for his guidance and help that expedited acquisition of my needs in the laboratory;

James Beck, Professional Officer of the Hydraulics Laboratory, for his technical assistance: starting from the design and fabrication of the apparatus until the end of the experimental work;

my friends for their help, suggestions and encouragement;

my wife, Jo and my children, Mae, Michelle, Michael and Mark: my inspiration, for their love, concern, understanding and patience;

and the Lord God Almighty: my Jehovah jireh, for giving me good health, strength, wisdom, protection, - ALL; without HIM this work will not be possible.
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A  area
a  radius of contact spots
B  correlation distance
b  radius of cylinder feeding the contact spot
c  interfacial gap due to distortion
CLA centre line average
CV  specific heat at constant volume
d  indentation diagonal
E  modulus of elasticity
E'  effective modulus of elasticity
F  constriction alleviation factor
g  temperature jump distance
H  microhardness
h  thermal conductance per unit area; height
J  Bessel function of the first kind
k  thermal conductivity
m  rms slope
n  number of contact spots
N_KN Knudsen number
P  contact pressure
q  heat flux
Q  total heat
R  constriction resistance
r  radius
rms  root mean square
T  temperature
tan θ  mean of the absolute slopes of the profiles
z  axial coordinate
Greek

\( \alpha \)  
wave length; standard deviation of the asperity heights; linear coefficient of thermal expansion; constant in the thermal conductivity equation of the specimen

\( \beta \)  
area coefficient of thermal expansion; coefficient in the temperature dependent conductivity of the specimen

\( \delta \)  
mean thickness of the gas gap

\( \gamma \)  
ratio of specific heats

\( \lambda \)  
mean free path of the gas molecules

\( \rho \)  
radius of curvature

\( \mu \)  
viscosity

Subscript

\( c \)  
contact

\( cd \)  
disc constriction

\( f \)  
fluid

\( j \)  
joint

\( m \)  
mean or average

\( n \)  
nominal

\( r \)  
radiation; real

\( v \)  
Vickers

\( 0 \)  
initial

\( 1 \)  
final; specimen identification

\( 2 \)  
 specimen identification
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CHAPTER 1
INTRODUCTION

Heat transfer at a solid to solid interface occurs in many engineering applications, ranging from the nuclear and aerospace fields to the cryogenic and microelectronic fields. The nuclear industry has produced a great deal of literature on heat transfer between fuel elements and their cans. The aircraft industry has long been interested in the heat transfer between structural members. The absence of a conducting fluid in space resulting to solid to solid heat transfer has led to extensive studies on contact phenomenon in the spacecraft program. The miniaturisation of electronic chips resulting to higher power densities and operating temperature and thus requiring greater capacities for heat dissipation has put more interest on the study of thermal contact conductance. Other important applications of interfacial heat transfer include heat transfer in electrical equipment, effects of contact resistance on the design of turbines and rotating machinery and cryogenic thermal insulation.

1.1 Definition of Thermal Joint Conductance and Thermal Contact Conductance

When the ends of two bars are in contact with each other as illustrated in figure 1.1, and a heat flux, $q$, is applied in the direction as shown, the variation of temperature along the lengths indicates an abrupt drop of temperature at the joint (shown by the dotted lines).

If the lines are extrapolated, the temperature drop, $\Delta T$, at the joint can be determined. The thermal joint conductance is then defined as:

$$h_j = \frac{q}{\Delta T} \quad 1.1$$

where the commonly used unit is watt/m$^2$ - K.
Figure 1.1 Temperature Variation along Two Bars Joined Together
The reciprocal of thermal joint conductance that in some cases is more convenient to use is termed as thermal joint resistance.

The abrupt drop of temperature at the joint is mainly due to the sudden reduction of the heat transfer area. The actual contact area at the joint is only a small percentage of the nominal area, i.e., the cross-sectional area of the bars. The main reason is that the surfaces in contact are composed of ridges and peaks. If they are to be examined microscopically the joint and the heat flow will appear as illustrated in figure 1.2 below.

Figure 1.2 Heat Flow through a Joint
Other factors like distortion of the surface as the heat is applied may lead to the reduction of the heat transfer area at the joint which may result to an increase in the resistance to heat flow.

There are three mechanisms of heat transfer across the interface in general. They are:

1. Heat conduction through the micro - contact spots
2. Heat conduction through the fluid occupying the voids in between the contacting surfaces
3. Thermal radiation across the gaps

All of the above are acting in parallel. This means that the thermal joint conductance is the sum of the individual conductance. In equation form the thermal joint conductance is shown below.

\[ h_j = h_c + h_f + h_r \]  

where:

- \( h_c \) = conductance due to the heat conduction through the micro - contact spots. This parameter is usually called the thermal contact conductance. It is sometimes called the solid spot conductance
- \( h_f \) = conductance due to the heat conduction through the voids in between the contacting surfaces. If gas is occupying the voids then the conductance is called the gas gap conductance
- \( h_r \) = conductance due to the thermal radiation across the interface

All of the above are principal contributors to the heat flow, however, they can be controlled in such a way that one or two can be minimised or made dominant over the others. Heat conduction through the micro - contact spots can be made dominant by conducting the experiment in vacuum. The second can be made dominant by minimising the contact pressure, i.e., the pressure
acting normal to the ends of the two bars, thereby pressing them against each other. The third is usually neglected by conducting the experiment at relatively not very high temperatures. In this work the temperature range used in the experiment is relatively not very high in such a way that the thermal radiation across the gaps is considered negligible.

1.2. Definition of Thermal Rectification

Figure 1.3 shows the situation if the direction of heat flow as illustrated in figure 1.1, is reversed. The temperature drop, $\Delta T_2$, may be different from $\Delta T_1$. Assuming other factors as the same, the difference between $\Delta T_1$ and $\Delta T_2$ represents the directional effect on the thermal joint conductance.
Positive thermal rectification is defined as an increase in thermal joint conductance as the heat flow is reversed. So the term thermal rectification can be applied to any situation where there is a directional effect depending on the reference of the direction of heat flow.

### 1.3. Use of Metallic Foils to Enhance Thermal Joint Conductance

Some engineering applications require reduction of the resistance to heat flow across an interface. Inserting a metallic foil in between the contacting surfaces can do enhancement of the thermal joint conductance. The presence of the foil would tend to increase the heat transfer area resulting to a lesser resistance to heat flow. The material must be a good thermal conductor otherwise the increase of the heat transfer area will be negated by its thermal insulating property. There are many types of material and many ways of introducing them in the interface. In this work only metallic foils were considered and they were simply placed in between and pressed as contact pressure was applied.

### 1.4 Measurement of Thermal Joint Conductance

An axial heat flow cut bar type of apparatus is used in measuring thermal joint conductance. Figure 1.4 presents a diagram of this type of apparatus (Peterson and Fletcher, 1990). It must be noted that the heat source and the heat sink are inside the vacuum chamber. The shape and form of existing apparatuses may differ from the others but their basic features and components are always the same.

The basic components of the apparatus are the following:

a) Heat source:

   It provides the heat that flows through the test specimens.

b) Heat sink:

   It absorbs the heat and then rejects it outside the vacuum chamber.

c) Lever-Weight assembly / Load cell
It presses the test specimens together.

d) Heat flux meter
   It measures the heat flux flowing through the test specimens.

e) Thermocouples
   They measure the temperature at different locations along the heat flow path.

f) Vacuum chamber
   It contains the test specimens and provides the space for the vacuum environment

g) Vacuum pump
   It creates the required vacuum in the vacuum chamber

h) Instrumentation and Data Acquisition system
   It takes readings of relevant parameters like temperature and vacuum pressure. The readings are then processed into the desired results.

An apparatus for measuring thermal contact conductance in vacuum and gaseous environment with provisions for reversal of the direction of heat flow was presented by Villanueva et al. (1996). It will be discussed in details in chapter 4.
Figure 1.4 Diagram of a Conventional Cut bar Type of Apparatus (Peterson and Fletcher, 1990)
1.5 Objectives of the Study

There are already many experimental studies on thermal contact conductance conducted during the past four decades. These will be comprehensively reviewed in the next chapter. The conventional type of apparatus has been used in these studies. Although the apparatus had been proven to work well in vacuum, it has features that can still be improved.

Thermal rectification of similar and dissimilar metals under vacuum has been reported in the thermal contact conductance literature. Most of the theoretical works are not sufficient to predict the occurrence of thermal rectification. There are conflicting conclusion regarding its occurrence in terms of the surface roughness. Some concluded that based on their experimental results positive thermal rectification occurs for similar materials if the heat flows from rough to smooth. Others claimed the opposite, while there are some who did not observe any rectification at all. The effect of oxide layer formed naturally on the contacting surface had not been considered in the past works.

There are existing experimental and theoretical studies on gas gap conductance. Equations for its prediction are presented in these works. These existing equations on gas gap conductance are independent of the heat flux and distortion of the contacting surfaces. With regards to the directional effect more experimental and theoretical works are needed in this area.

Although numerous studies had been done on the effect of interstitial materials on thermal contact conductance, the following are areas that still need more works:

a) Experimental work on the existence of an optimum foil thickness
b) Theoretical work that will explain the enhancement mechanism of interstitial materials

Thus, the objectives of the study are:
1) To design and construct an apparatus that is capable of performing accurately and reliably the following types of experiments:
   a) Thermal rectification of similar and dissimilar materials under vacuum;
   b) Effect of interstitial materials on thermal contact conductance;
   c) Directional effect on gas gap conductance.

2) To develop a theoretical model that could predict and quantify the thermal contact conductance in both directions of heat flow.

3) To incorporate the effect of naturally formed oxide layer on thermal contact conductance.

4) To perform experimental work on the effect of metallic foil on thermal contact conductance, verify the existence of an optimum thickness, and make some comparisons with the results based on a slightly modified theory (incorporation of the effect of oxide layer for aluminium foil).

5) To perform experimental work on the directional effects on gas gap conductance and compare the results with the slightly modified theory (consideration of the effect of distortion).
CHAPTER 2
REVIEW OF LITERATURE

Thermal conductance at the joint of two contacting surfaces has been studied extensively during the past four decades. This illustrates the recognition of the importance of predicting thermal joint conductance in many engineering applications such as in the aerospace, nuclear, electronics as well as in any other heat transfer systems. The trend towards the use of high power densities and temperature in order to improve system thermal efficiencies has led to a greater attention on thermal joint conductance in heat transfer analysis. Also in the electronics industry, the power density to volume ratio of the electronics chips has increased tremendously requiring a more efficient and reliable heat dissipation system.

Several studies relevant to the area of research have been reported in the literature. They are grouped under the following:

1. Thermal rectification of similar and dissimilar metals under vacuum.
2. Thermal rectification of dissimilar metals in an inert gas environment.
3. Effect of interstitial materials on thermal joint conductance.

2.1 Thermal Rectification of Similar and Dissimilar Metals under Vacuum

Starr (1936) first observed thermal rectification. However, it was given greater attention starting only in the 1950’s. The early works of Barzelay (1954,1955) noted that when steel and aluminium specimens were in contact the conductance was dependent upon the direction of heat flow. They observed that the conductance from aluminium to stainless steel was appreciably greater than that from stainless steel to aluminium. The tests were performed in air at atmospheric pressure and inverting the specimens did the reversal of heat flow.

Rogers (1961) did his experimental work on thermal rectification of dissimilar metals in an apparatus where the heat flow direction can be reversed without disturbing the specimens. The apparatus had a heating
element and cooling coil at each end of the experimental column. It can perform an experiment under vacuum. The design was adopted since the conductance was noted to be very sensitive to changes in contact configuration. He observed the occurrence of thermal rectification and that the conductance is higher in atmospheric air than in vacuum. He suggested that the thermal rectification could be due to a potential barrier formed in the joint that might reduce the drift of free electrons in one direction and increase it in the other. He dismissed the idea that warping may cause thermal rectification. Williams (1961) on his comments to Rogers' paper attributed it to surface contamination.

Clausing (1966) proposed a theory that used a macroscopic model to explain the directional effect of dissimilar metals. His model explained that when heat is applied, the contacting metals will be at different temperatures, i.e., one is hot the other is cold depending on the direction of heat flow. The differences in temperature resulted to differences in thermal strain leading to a macroscopic contact area that would be smaller or larger. In his experimental work, he used specimens with spherically shaped ends to simulate his macroscopic model. However, he did not mention how his model could explain the directional effect of nominally flat rough surfaces.

Lewis and Perkins (1968) applied the macroscopic spherical cap model of Clausing (1966) to a microscopic model of the surfaces of contacting dissimilar metals. They presented two physical models: (a) a spherical cap model which was patterned after Clausing's model, and (b) flat rough model. The prediction could only be done after categorising the interface with the physical models. According to them for a flat rough surface, the contact conductance will be highest when heat flows from the metal of high thermal conductivity to that of low thermal conductivity. They presented experimental results; however, they did not present a method of quantifying the contact conductance using the theoretical model. Their experiments were performed in vacuum.
In the works of Thomas and Probert (1970), they found out that the directional effect decreased with increasing heat flux that was contrary to Clausing’s findings. They got results that showed an increase in directional effect with number of reversals, which was contrary to Williams’ suggestion (Williams, 1967). Their results on stainless steel and aluminium specimens agreed with Lewis and Perkins’ predictions, i.e., the conductance was greater when the heat flow was from aluminium to stainless steel. They made suggestions that the work of Moon and Keeler (1962) appeared to hold most promise although they recognised the problem of applying it due to the lack of the knowledge of the work functions of the contacting surfaces. They concluded that none of the geometrical theories for the directional effect of previous investigators were able to give a quantitative explanation of their results.

Stevenson et al. (1991) used a model consisting of two elastic spheres to explain the basic phenomenon of thermal rectification. Their experimental results indicated that the thermal rectification was a function of both the properties and the surface parameters. Thermal rectification was observed from the rough surface to the smooth surface for similar materials, and from stainless steel to nickel for dissimilar metals. According to them their results showed that surface roughness was of secondary importance. Like the previous works, they did not demonstrate how to quantify the thermal rectification using the theoretical model. Aside from that they did not illustrate how to relate the two elastic spheres of the model to the physical characteristics of the contacting surfaces.

2.2 Directional Effect on Gas Gap Conductance Using Dissimilar Metals

Directional effect (thermal rectification) of dissimilar metals in a gaseous environment is one of the many areas of thermal joint conductance that is not given much attention. At the moment, there are only two specific works done on this area.
Jeevanashankara et al. (1990) found out from their experimental results that rectification occurred from aluminium to stainless steel. Their tests were conducted in air and mean temperature of about 200°C and 120°C for the aluminium to stainless steel and stainless steel to aluminium heat flow respectively. The conductance at different contact pressure was obtained. The tests were conducted at relatively low contact pressure (< 0.5 MPa). In their analysis, they attributed the rectification mainly to the sensitivity of the thermal conductivity of air to temperature changes.

Madhusudana (1993) offered an alternative explanation of rectification at low joint pressures with an interstitial gas. He presented data illustrating the dominance of gas gap conduction over solid spot conduction at low joint pressures. The gas gap conduction is known to be a strong function of the gas thermal conductivity. According to him, gases that are highly dependent on temperature would cause rectification. For two contacting dissimilar metals, the mean junction temperature varies as the heat flow is reversed. The variation would result to a change in gas thermal conductivity and thus the thermal joint conductance.

There are several experimental and theoretical works done on gas gap conductance. Some of these works are very relevant to the studies of thermal rectification of dissimilar metals in gaseous environment. They are presented in section 8.1 of chapter 8.

2.3 Effect of Interstitial Materials on Thermal Joint Conductance

Numerous research works had been done on this area. Fletcher et al. (1969) in their early works, did an experimental investigation that determined the thermal isolation characteristics of some low-conductance interstitial materials. The experiments were conducted in a vacuum environment. The test specimens used were made of aluminium materials. The waviness and roughness of the contacting surfaces were approximately 25 and 5 μin. respectively. Different types of insulating materials were tested. They found out that the resistance to heat transfer was increased by factors from 2 to
1000 as a result of the presence of interstitial material in between the contacting surfaces.

Gyorog (1970) performed a study similar to Fletcher’s, however, he used stainless steel 304 as the material for the test specimens and different isolation materials. In addition, he did flange tests to demonstrate thermal isolation with the insulating interstitial materials. He presented a dimensionless correlation for predicting thermal contact resistance with screen wire as the interstitial material.

Mikic and Carnasciali (1970) carried out an analytical and experimental work on the effect of thermal conductivity of plating material on thermal contact resistance. They developed a model for predicting the contact resistance. Their experimental results agreed well with the model. They concluded that for surfaces where microscopic constriction was the predominant resistance, plating both the contacting surfaces would significantly reduce the contact resistance.

Yovanovich (1972) presented results of a series of experiments on the effect of lead, tin, aluminium, and copper foils on the thermal resistance of a lathe turned surface in contact with an optically flat surface. The thickness of the foil used ranged from 10 to 500 µm. All foils had reduced the contact resistance. He found out also from the results that there was a foil thickness where the joint resistance was minimum. He defined it as the optimum foil thickness. He then proposed that the effectiveness of the foil could be ranked by means of the ratio of the thermal conductivity to the material hardness; the larger the ratio the greater would be the reduction of the bare joint resistance.

Fletcher (1972) formulated a dimensionless conductance that he applied to the results of previous investigations on thermal control materials or interstitial materials. He then made comparison of the effectiveness of interstitial materials using the formula. In his analysis, he classified the thermal control materials into four: 1) synthetics and processed natural sheets; 2) ceramic sheets and powder; 3) metallic foils and screen; 4) greases and oils. The numerical value of the dimensionless parameter would indicate
the thermal isolation or enhancement, compression strength, durability and weight of the materials. Majority of the materials he reviewed fitted to the classifications, however he did point out that there were exceptions.

The works of Snaith et al. (1984) and O'Callaghan et al. (1983) presented a procedure of predicting the appropriate filler thickness for minimising thermal contact resistance between flat non-wavy surfaces. Tin foil was used as the filler material in their experiment. It was coated on one surface of the two contacting surfaces. In their analysis, they considered two cases, i.e.; the filler thickness is less than the surface roughness while the other greatly exceeds. They simplified their theoretical model by applying assumptions and approximations. Their formula for determining thermal contact resistance for a joint with an optimum filler material was the same as the bare joint expression except that the hardness to be used is of the filler material. Their experimental results showed substantial reduction in contact resistance with the tin coating compared with the bare junction. They also indicated the existence of an optimum filler thickness although they did not agree well with the theoretical model.

Snaith et al. (1984) made an assessment of the thermal performance of interstitial materials. They classified the interstitial materials into three groups: 1) metals; 2) non-metals; 3) grease, oils and other materials. Procedures of rating the effectiveness of interstitial materials proposed by previous investigators were presented and discussed. They mentioned also that in design problems associated with pressed metallic joints the selection of interstitial materials is not only based on the thermal performance and that other factors should be considered.

Antonetti and Yovanovich (1985) developed a thermomechanical model for nominally flat, rough contacting surfaces coated with a metallic layer. The equation for predicting the thermal conductance was reduced to an equivalent bare joint by employing an effective hardness and an effective thermal conductivity. The model agreed well with their experimental results. Their results indicated increasing enhancement with increasing coating thickness at
all contact pressures. They specified a lower and an upper bounds thickness of coatings. The lower bound was no coating and the upper bound was infinite coating. Their work did not mention the existence of an optimum thickness unlike with the works of Snaith and O’Callaghan.

Antonetti and Yovanovich (1985) applied the thermomechanical model for coated contacts that they previously developed (Antonetti and Yovanovich, 1988) to a common electronics packaging problem specifically heat transfer across aluminium joint. They presented graphs and figures obtained by using the theoretical model. They proposed that the performance of coated joints could be ranked by the ratio of the effective thermal conductivity over the effective microhardness of soft layer on harder substrate raise to the power 0.93.

Peterson and Fletcher (1990) conducted an experimental investigation on thermal contact conductance and effective thermal conductivity of anodised coatings. The specimens were made of Aluminium 6061-T6. They tested one chemically polished specimen and seven specimens with anodised coatings of varying thickness against a single unanodised aluminium surface. The experimental results indicated a decreased in the overall joint conductance with increasing thickness of the anodised coatings and increased with increasing contact pressure. Based on them, they developed a dimensionless expression relating the overall joint conductance to the coating thickness, surface roughness, contact pressure, and the properties of the aluminium specimen.

Kang et al. (1990) conducted experiments on the enhancement of the thermal contact conductance of aluminium 6061-T6 specimens by coating the contacting surfaces. Lead, tin, and indium were employed as the coating materials. Four different thicknesses were used for each of them. The results confirmed the existence of an optimum thickness that was in the range of 2.0 to 3.0 μm for indium, 1.5 to 2.5 μm for lead, and 0.2 to 0.5 μm for tin. Based upon the obtained data, they were inclined to deduce that the hardness of the coating materials appeared to be most significant parameter in ranking the
substrate and coating material combinations. However, they mentioned that more data were needed to substantiate the hypothesis. Their results also showed that the enhancement effect was greatest at low contact pressure and decreased significantly with increase in the contact pressure.

Babus'haq et al. (1991) reviewed previous investigations of controlling thermal contact conductance by the use of interstitial materials. They developed a mathematical model that could describe the behaviour of the pressed contact resulting from the simultaneous applications of mechanical and thermal loads. The computation involved the use of a linked set of computer codes. Comparing the predictions with experimental measurements validated the model. They found out that for duralumin and titanium alloy contact, the aluminium cooking foil proved to be a better insert compared with the more expensive, commercially supported thermal control materials for enhancing thermal contact conductance.

Sauer et al. (1971) and Sauer (1992) reported the enhancement of the contact conductance by the use of aluminium foil. The material for the test specimens was aluminium 2024-T4. The surface roughness of the bare junction was 0.77 μm and the foil thickness was 640 μm. The contact pressure range was from 1 to 4 MPa. The conductance increased by a factor of approximately 3 over the complete range of pressures. However, the bare junction was tested in air rather than in vacuum.

Lambert et al. (1993) investigated the thermal contact conductance of anodised coatings synthesised at different bath temperatures and in different electrolyte solutions. The testing was done using anodised aluminium 6101-T6 and uncoated aluminium A356-T6 specimens. Based on the experimental results, they concluded that the best results were obtained for coatings grown at low temperature. They reasoned out that the lower the bath temperature the lower was the activity of the electrolyte as the film grows resulting in an anodised coating of higher density, higher thermal conductivity, and higher thermal contact conductance although the microhardness was higher.
Lambert and Fletcher (1993) did an extensive review of previous works on the effect of metallic coatings and films on the thermal contact conductance of junctions. They remarked that for microelectronics applications only surface treatments and coatings were deemed suitable. They enumerated and discussed different coating materials, their properties, and desirable and undesirable characteristics. Prediction techniques of different investigators were also mentioned. They presented suitable coatings for nickel-plated copper module cards and discussed their advantages and disadvantages. They identified silver, gold, and copper to provide the far greater increases in contact conductance than the other metals compatible with the nickel-plated copper.

Marotta et al. (1994) made an assessment on metallic and non-metallic coating materials for the enhancement or isolation of thermal contact conductance of metallic interfaces for microelectronics applications. They presented new experimental thermal contact conductance data for microelectronics applications. They compared several metallic coatings deposited by different techniques and arrived to the following observations:

**Metallic Group** - Electroplated silver had the highest thermal contact conductance while flame sprayed silver the lowest.

**Non-metallic Group** - Low temperature, sulfuric electrolyte anodised coating had the highest thermal contact conductance compared with bare aluminium junction while the chromic anodised coating had the lowest.

**Ceramic Group** - Titanium nitride provided the highest thermal contact conductance while beryllium oxide showed reasonable performance.

Oouedel et al. (1994) derived an expression by correlating the experimental data for four metallic foils (aluminium, tin, lead, and copper) inserted between aluminium 6061-T6 surfaces in a vacuum environment. The formula expressed the thermal contact conductance with foils as functions of the thermal contact conductance of the bare joint, hardness and thermal
conductivity of the foil and bare joint materials, and the profile of the bare joint surfaces. The expression was independent of the modulus of elasticity however, they specified that it is an important parameter and must be introduced into the equation if the ratio of contact pressure over roughness is high.

Madhusudana and Villanueva (1996) obtained an expression for the effectiveness of foils by correlating experimental data of previous investigations. The correlation obtained depends strongly on the relative conductivities and the relative hardness of the foil and the base materials and is also influenced by the ratio of the foil thickness to the surface roughness.

Villanueva and Madhusudana (1996) did an experimental work on the effect of metallic foils on thermal contact conductance. The experiment was conducted in vacuum. The foils used were aluminium and gold. The materials for the test specimens were NILO 36 and stainless steel SS 304. The roughness of the specimens ranges from 0.5 to 5.7 µm. They observed a remarkable increase in thermal contact conductance when there is foil in between the contacting surfaces.

The study that will be presented in the next chapters is focused on research areas that are relevant to the previous works that were discussed above:

a) The development of a model that can predict and quantify the occurrence of thermal rectification. The model also resolves the conflicting observations regarding occurrence of thermal rectification of similar materials in terms of surface roughness (some observed positive thermal rectification if the heat flows from rough to smooth; others claimed the opposite; while there are some who did not observe any rectification at all).

b) The design and construction of an apparatus that can perform accurately and reliably experiments on thermal rectification, effect of
metallic foils on thermal contact conductance, and gas gap conductance.

c) Conduct of experiments on the effect of metallic foils and verification of the existence of an optimum thickness.

d) Conduct of experiments that will validate the present theories on gas gap conductance.
CHAPTER 3
THEORETICAL MODEL OF THE THERMAL RECTIFICATION

Thermal rectification (also termed as directional effect) on thermal contact conductance is the change of the conductance as the direction of heat flow is reversed. It is a phenomenon that was first reported by Starr (1936). A number of studies both theoretical and experimental are done on this area. However conflicting results are commonly observed specially on the thermal rectification of similar materials in a vacuum environment. In this case some investigators claim that there is an increase in thermal contact conductance if the heat flows from the specimen of rougher surface to the specimen of smoother surface. Others claim the opposite while there are some who did not observe any thermal rectification at all. The theoretical model to be presented in this chapter can explain the conflicting observations. A computer program is developed based on the theoretical model. The program can calculate the thermal conductance in both directions and thus predicts the occurrence of thermal rectification.

3.1 Theoretical Background

It was shown in figure 1.2 of Chapter 1 that two contacting nominally flat surfaces actually touch only at a few discrete spots. This results in a complicated and three dimensional temperature distribution. In the theoretical investigation of the resistance to heat flow through the joint, the simplest and the most basic situation which can be considered is the resistance associated with a disc in a semi - infinite medium. This is illustrated in figure 3.1. The exact solution to this case is well known (Carslaw, 1959; Holm, 1958). The following assumptions were used in obtaining the solution:

a.) The constriction is small compared with the other dimensions of the medium in which heat flow occurs;
b.) The constriction of heat flow lines is not affected by the presence of other contact spots;

c.) There is no conduction of heat through the gap surrounding the contact spot;

Figure 3.1 Circular Constriction in Half Space
d.) The contact area, \( (0 < r < a) \), is maintained at constant temperature, \( T_c \).

Based on the total heat flow the disc constriction resistance is

\[
R_{cd} = \frac{1}{4ak}
\]

3.1

The total resistance of a single contact spot i.e., two semi - infinite media contacting over a disc of radius \( a \), would be twice the above value.

As shown in figure 3.2 there can be several contact spots in a real joint. In order to be able to solve the problem of determining the thermal contact resistance of the joint, the following assumptions were introduced:

1.) Each contact spot of radius \( a_i \) is fed by a cylinder of larger radius \( b_i \);
2.) No cross flow of heat between the adjacent cylinders;
3.) No heat flow across the gap between the adjacent contact spots, i.e., the contact spot is surrounded by a vacuum in the contact plane;
4.) The sum of the areas of all of the contact spots is equal to the real contact area, \( A_r \);
5.) The sum of cross - sectional areas of all the feeding cylinders is equal to the nominal area of contact, \( A_n \).

Figure 3.2 shows also the idealised configuration of the contact plane where a single contact spot is modelled in a cluster of spots.

There are several works dealing with the solution to the problem. Using the result of the analysis presented by Cooper et al. (1969), the hypothetical temperature drop, \( \Delta T_c \), is given below.

\[
\Delta T_c = \frac{Q}{2ka} F\left(\frac{a}{b}\right)
\]

3.2
Constriction Bounded by a Semi-Infinite Cylinder

Figure 3.2 Idealised Configuration of the Contact Plane
where:

\[ k = \text{harmonic mean of the thermal conductivities of the contacting surfaces, W/m-K} \]

\[ = \frac{2k_1k_2}{k_1 + k_2} \]

\[ Q = \text{total heat flow, W} \]

\[ F(a/b) = \text{constriction alleviation factor} \]

The thermal contact conductance is equal to the heat flux divided by the junction temperature drop,

\[ h_c = \frac{Q}{A_n \left( \frac{1}{\Delta T_c} \right)} = \frac{2ka}{\pi b^2 F \left( \frac{a}{b} \right)} \]

where:

\[ F \left( \frac{a}{b} \right) = \frac{8}{\pi} \left( \frac{b}{a} \right) \sum_{n=1}^{\infty} \frac{\sin(\alpha_n a)J_1(\alpha_n a)}{(\alpha_n b)^3 J_0(\alpha_n b)} \]

\[ = \text{constriction alleviation factor as mentioned earlier} \]

Several authors have evaluated the value of the constriction alleviation factor. The equation as derived by Roess, Gibson, and Negus and Yovanovich (as presented by Madhusudana (1996)) are shown below:

\[ F_{\text{Roess}} = 1 - 1.4093(a/b) + 0.2959(a/b)^3 + 0.05254(a/b)^5 + \ldots \]

\[ F_{\text{Gibson}} = 1 - 1.4092(a/b) + 0.3380(a/b)^3 + 0.0679(a/b)^5 + \ldots \]

\[ F_{\text{N.Y}} = 1 - 1.4098(a/b) + 0.3441(a/b)^3 + 0.0435(a/b)^5 + \ldots \]

The constriction alleviation factor approaches 1 as the radius \( b \) approaches infinity. This means the apparent area approaches infinity.
The temperature drop, $\Delta T_c$, is the same in all channels. This implies that all contacts should have the same value of \{2k$\Delta T_c\}$, which is \{Q/(a/F)\}. Consequently the total heat flow $Q$ over the area $A_n$ must be subdivided into $Q_1$ through contact 1, $Q_2$ through contact 2,..........., $Q_i$ through contact $i$. Neglecting variation in $F_i$,

$$\frac{Q}{a} = 2k\Delta T_c = \frac{Q_1}{a_1 \frac{F_1}{F}} = \frac{Q_2}{a_2 \frac{F_2}{F}} .............. = \frac{Q_i}{a_i \frac{F_i}{F}}$$

3.4

Since

$$Q = Q_1 + Q_2 + Q_3 +..............+ Q_m$$

We get

$$2k\Delta T_c \left(\frac{a}{F}\right) = 2k\Delta T_c \sum_{j=1}^{m} \left(\frac{a_j}{F_j}\right)$$

This gives

$$\frac{a}{F} = \sum_{j=1}^{m} \left(\frac{a_j}{F_j}\right)$$

then

$$Q_i = Q \frac{\left(\frac{a_i}{F_i}\right)}{\sum_{j=1}^{m} \left(\frac{a_j}{F_j}\right)} = Q \frac{a_i}{\sum_{j=1}^{m} a_j}$$

3.5
Also, the total flow area \( A_n \) can be considered as composed of areas \( A_{n1}, A_{n2}, A_{n3}, \ldots, A_{nm} \), of which each is supplying heat flow to corresponding contacts, where

\[
A_{ni} = A_n \frac{Q_i}{Q} = A_n \frac{a_i}{\sum_{j=1}^{m} \left( \frac{a_j}{F_j} \right)} = A_n \frac{a_i}{\sum_{j=1}^{m} a_j} \tag{3.6}
\]

In this case the contacts are considered “appropriately distributed”, i.e., the contact point is at the centre of the adiabatic cylinder.

Since \( \Delta T_c \) is common for the entire multiple contact region, \( h_c \) is the same for any of the individual channels, i.e.,

\[
h_c = \frac{Q}{\Delta T_c} = \frac{1}{A_n} \sum_{i=1}^{m} \frac{Q_i}{\Delta T_c} = \frac{2k}{A_n} \sum_{i=1}^{m} \frac{a_i}{F_i} \tag{3.7}
\]

According to Yovanovich (1975) for an appropriately distributed contact, the following simple expression closely approximates the constriction alleviation factor \( F_i \):

\[
F_i = \left( 1 - \frac{a_i}{b_i} \right)^{1.5} \tag{3.8}
\]

If we let

\[
\sum_{i=1}^{m} \frac{a_i}{A_n} = n a_m
\]

where:

\( a_m = \) mean radius of the contact spots

\( n = \) number of contact spots per unit area
then
\[ h_c = \frac{2kna_m}{F} \]  \hspace{1cm} 3.9

The values of \( n \) and \( a_m \) can be obtained by surface and deformation analyses. Madhusudana (1996) gives a detailed presentation of the derivation of \( na_m \) which leads to the following equation:

\[ na_m = \left( \frac{1}{4\pi} \right) \left( \frac{\tan \theta}{\sigma} \right) \exp \left[ - \left\{ \text{erfc}^{-1} \left( \frac{2A_r}{A} \right) \right\}^2 \right] \]  \hspace{1cm} 3.10

substituting the above into equation 3.9 would result to

\[ h_c = \left( \frac{1}{F} \right) \left( \frac{1}{2\pi} \right) \left( \frac{k\tan \theta}{\sigma} \right) \exp(-X) \]  \hspace{1cm} 3.11

where:

\[ X = \left\{ \text{erfc}^{-1} \left( \frac{2A_r}{A} \right) \right\}^2 \]

For fully plastic deformation and with the assumption that all asperities in contact are deforming at the same flow pressure, \( H \), the following relationship holds:

\[ \frac{A_r}{A} = \frac{P}{H} \]  \hspace{1cm} 3.12

where \( H \) is the microhardness of the softer of the two contacting materials. The above equation does not consider conservation of volume. The corresponding error is negligible at low contact pressure. For larger loads where the displaced volume is accounted, Mikic (1974) proposed that \( P/H \) is replaced by \( P/(P + H) \).
If we substitute equation 3.12 into equation 3.11, the expression for the solid spot thermal conductance becomes

\[
h_c = \left( \frac{1}{1 - \frac{1}{2\pi}} \right) \frac{ktan\theta}{\sigma} \exp \left[ - \left\{ \text{erfc} \left( \frac{2P}{H} \right) \right\}^2 \right]
\]

3.13

A similar result shown below was obtained by Mikic (1974).

\[
h_c = 1.13 \frac{ktan\theta}{\sigma} \left( \frac{P}{H} \right)^{0.94}
\]

3.14

For elastic deformation, Mikic (1974) derived the following equation:

\[
h_c = 1.55 \frac{ktan\theta}{\sigma} \left( \frac{P\sqrt{2}}{E'tan\theta} \right)^{0.94}
\]

3.15

The type of deformation whether elastic or plastic is determined by using a plasticity index. Greenwood (1967) defined it as

\[
\psi_g = \left( \frac{E'}{H} \right) \frac{\sigma}{\sqrt{r}}
\]

3.16

where

\[r = \text{radius of curvature of spherical asperities}\]
\[H = \text{hardness of the softer of the contacting specimens}\]
\[\sigma = \text{standard deviation of profile height distribution}\]
\[E' = \text{effective elastic modulus of the contacting specimens}\]
\[= 2\left[ (1-v_1^2)/E_1 + [(1-v_2^2)/E_2] \right]^{-1}\]
Surfaces with plasticity index greater than 1, which cover most manufactured surfaces, will have plastic contact at the lightest loads. By careful polishing, surfaces can be prepared to have a plasticity index less than 0.7, the limit below which the contacts are predominantly elastic.

The random surface model of Whitehouse and Archard (1970) and the analysis of Tabor (1975) result to a similar plasticity index as given below:

$$\psi_{A} = \left(\frac{E'}{H}\right)(\sigma/B)$$  \hspace{1cm} 3.17

in which $B$ is the correlation distance corresponding roughly to the spacing between asperities of equal heights. Tabor (1975) suggested that plastic deformation occurred when the plasticity index attained the value of 1.

The analysis of Mikic (1974) shows that it is the slope of the asperities that controls the mode of the deformation for a given pair of materials in contact. He proposed the following index:

$$\gamma = \frac{H}{E'|\tan\theta|}$$  \hspace{1cm} 3.18

According to him the deformation is predominantly elastic for $\gamma > 3$ and predominantly plastic for $\gamma < 0.33$. For most engineering surfaces $\gamma$ is less than 0.1.

Tien as mentioned by Madhusudana (1981), carried a dimensional analysis for nominally flat rough surfaces. He obtained the following relationship similar to equation 3.14:

$$h\frac{\sigma}{k} = f m^g \left(\frac{P}{H}\right)^d$$  \hspace{1cm} 3.19
where:

\[ m = \text{slope, root mean square (rms)} \]
\[ f, g, d = \text{constants to be determined from experimental results} \]

In the determination of the constants, he considered the following:

1) The equation is applicable to similar materials only since dissimilar materials may have complications such as directional effect

2) The surfaces are nominally flat if the rms roughness is greater than one-tenth of the total flatness deviation

3) The exponent \( d \) is obtained by plotting \( \left( \frac{h_0}{k} \right) \) vs \( \left( \frac{P}{H} \right) \) on a log-log basis

4) The exponent \( g \) is assumed to be equal to 1

With the above considerations the values of \( d \) and \( f \) were estimated as 0.85 and 0.55 respectively. The equation can then be written as

\[
\frac{h_0}{k} = 0.55m \left( \frac{P}{H} \right)^{0.85}
\]

There had been several correlations proposed over the past three decades. Most of them have the same form as given by equation 3.20.

### 3.2 Theoretical Model for the Thermal Rectification of Similar/Dissimilar Metals in a Vacuum Environment

The microscopic contact of two asperities is modelled as contact of two spheres. Figure 3.3 shows the contact of two asperities with spherical tips before heating. The radii are \( r_{01} \) and \( r_{02} \). The radius of the asperity can be obtained by relating it with the rms roughness, \( \sigma \), and slope, \( m \).
Figure 3.3 Contact of Two Asperities with Spherical Tips
3.2.1 Radii of Contacting Spherical Tips Before Heating

For Specimen 1

Using figure 3.3 let the average slope $m_{01}$ equal to the slope as obtained by surface analysis. Then

$$m_{01} = \tan\left(\frac{\theta_{01}}{2}\right) \quad \text{3.21}$$

From the figure, we can solve

$$x_1 = \frac{\sigma_{01}}{m_{01}} \quad \text{3.22}$$

where $x_1$ is obtained by drawing a line parallel to the tangent of the point of contact and $\sigma_{01}$ away from it.

$$\sin\left(\frac{\theta_{01}}{2}\right) = \frac{\sigma_{01}}{\sqrt{\sigma_{01}^2 + x_1^2}} \quad \text{3.23}$$

Also

$$\sin\left(\frac{\theta_{01}}{2}\right) = \frac{1}{2} \frac{\sqrt{\sigma_{01}^2 + x_1^2}}{r_{01}} \quad \text{3.24}$$

Combining equations 3.23 and 3.24

$$\frac{\sigma_{01}}{\sqrt{\sigma_{01}^2 + x_1^2}} = \frac{1}{2} \frac{\sqrt{\sigma_{01}^2 + x_1^2}}{r_{01}} \quad \text{3.25}$$
To eliminate $x_1$, equation 3.22 is plugged into equation 3.25 resulting to

\[
\frac{\sigma_{o1}}{\sqrt{\sigma_{o1}^2 + \left(\frac{\sigma_{o1}}{m_{o1}}\right)^2}} = \frac{1}{2} \sqrt{\sigma_{o1}^2 + \left(\frac{\sigma_{o1}}{m_{o1}}\right)^2} r_{o1}
\]

Rearranging and simplifying equation 3.26 will result to the following expression:

\[
r_{o1} = \frac{1}{2} \sigma_{o1} \left(\frac{m_{o1}^2 + 1}{m_{o1}^2}\right)
\]

For Specimen 2

Using the same steps as previously given, the expression for the radius $r_{o2}$ is

\[
r_{o2} = \frac{1}{2} \sigma_{o2} \left(\frac{m_{o2}^2 + 1}{m_{o2}^2}\right)
\]

3.2.2 Radii of Contacting Spherical Tips with Heating

The two spheres are subjected to the simultaneous application of mechanical and heat loads. A schematic diagram (Figure 3.4) shows the temperature distribution and deformation of the contacting asperities due to the loads.
Figure 3.4 Relative Temperature Distribution and Deformation of Two Contacting Asperities with Spherical Tips
The main objective of the model is to determine the contact area for a particular heat flow direction. Then the heat flow is reversed and the contact area obtained is compared with that for the opposite direction. If the contact areas of the two directions differ with each other, thermal rectification does occur.

The exact deformation of the contacting spheres due to the mechanical and heat loads is mathematically difficult to achieve. However by using the following assumptions an approximation of the contact area can be calculated:

1) The two loads, i.e., mechanical and heat loads, are treated separately with one being superimposed on the other. Although the two loads are physically applied simultaneously with interrelated effects, the calculation is facilitated by considering the effect of the heat load first, then the output is used as part of the input for the mechanical load effect calculation and the process is repeated until the results have stabilised.

2) Figure 3.4 displays the relative temperature values depending on the direction of heat flow. For top to bottom heat flow the isotherms $T_A$, $T_B$ and $T_C$ of asperity 1 and $T_N$, $T_O$ and $T_P$ of asperity 2 are decreasing in value. The opposite is expected if the heat flow is reversed. The higher temperature areas expand more than the lower temperature areas. It is assumed in the model that the spherical shape is retained after the expansion so that the Herztian equation can be applied. The expansion is constrained as shown by the dotted lines in figure 3.5. This is because the base of the asperity is constrained by the bases of the adjacent asperities. It must be noted that the expansion of asperity 1 is different from asperity 2 depending on the direction of heat flow. For 1 to 2 heat flow as illustrated in figure 3.4, the expansion of asperity 1 is greater at the base and decreases while going to the tip whereas for asperity 2 it is greater at the tip then decreases while going to the base. This is because the temperature
of asperity 1 is higher at the base and lower at the tip. For asperity 2 the temperature is higher at the tip and lower at the base. The opposite will happen if the heat flow is reversed.

3) The temperature used for the calculation is the extrapolated temperature. For asperity 1, as an example, $T_1$ (Please refer to Figure 1.1 of chapter 1) is used while $T_2$ for asperity 2. The extrapolated temperature represents the average temperature of the tip of the asperity. This is the basis in the calculation of the thermal contact conductance and in order to be consistent other calculations should also be based on this value.

4) The original dimensions, i.e., before heating, are all based at an ambient temperature of 20°C. The ambient temperature of 20°C is representative of the ambient temperature of the area where the experiments were conducted.

5) The deformation due to the mechanical load follows the Herztian equation for two contacting spheres.

6) The variation of thermal conductivity with temperature is taken into account.

With the above considerations, the following derivations are presented:

**For Asperity 1**

Let

$$A_{01} = \text{the original area which is bounded as shown in figure 3.5 by the line } x_1 \text{ and the circular arc of angle } \theta_{01}$$

$$A_{11} = \text{the area after thermal expansion which is bounded as shown in figure 3.5 by the line } x_1 \text{ and the circular arc of angle } \theta_{11}$$
Then from figure 3.5

\[
A_{01} = \frac{1}{2} \theta_{01} r_{01}^2 - \frac{1}{2} x_{1} r_{01} \cos \theta_{01}
\]

\[3.29\]

\[
A_{11} = h_{11} x_{1} + \left[ \frac{1}{2} \theta_{11} r_{11}^2 - \frac{1}{2} x_{1} r_{11} \cos \theta_{11} \right]
\]

\[3.30\]

\[
\Delta A_{1} = A_{11} - A_{01} = \beta_{1} A_{01} \Delta T_{1}
\]

\[3.31\]

= one of the two cross-hatched areas of figure 3.5. the two areas are actually equal

where \( \beta \) is the area coefficient of thermal expansion.
Figure 3.5 Two Dimensional Thermal Expansion of Asperity 1
In most metals, it is the linear coefficient of thermal expansion, $\alpha$, that is commonly known. It can be shown that the area coefficient of thermal expansion is equal to twice the linear coefficient of thermal expansion (see Appendix A).

Therefore,

$$\beta = 2\alpha$$

Plugging the value $\beta = 2\alpha$ into equation 3.31 will result to

$$\Delta A_1 = A_{11} - A_{01} = 2\alpha A_{01} \Delta T_1$$  \hspace{1cm} 3.32

To eliminate $h_1$ and $\theta_{11}$, using Fig. 3.5

$$\sigma_{01} - h_1 = r_{11} - \sqrt{r_{11}^2 - x_1^2}$$  \hspace{1cm} 3.33

$$\theta_{11} = \sin^{-1}\left(\frac{x_1}{r_{11}}\right) = \frac{x_1}{r_{11}} + \frac{1}{6}\left(\frac{x_1}{r_{11}}\right)^3 + \frac{3}{40}\left(\frac{x_1}{r_{11}}\right)^5 \hspace{1cm} 3.34$$

For $x_1 < r_{11}$, the third and higher terms of equation 3.34 can be neglected resulting in

$$\theta_{11} = \sin^{-1}\left(\frac{x_1}{r_{11}}\right) = \frac{x_1}{r_{11}} + \frac{1}{6}\left(\frac{x_1}{r_{11}}\right)^3$$  \hspace{1cm} 3.35

$$\cos \theta_{11} = \frac{\sqrt{r_{11}^2 - x_1^2}}{r_{11}}$$  \hspace{1cm} 3.36
Substituting equations 3.33, 3.35, 3.36, 3.37 into equation 3.30 and rearranging, the result is the equation shown below.

\[
\left( \sigma_{01} - r_{11} + \sqrt{r_{11}^2 - x_1^2} \right) x_1 + \frac{1}{2} \left[ \frac{x_1}{r_{11}} + \frac{1}{6} \left( \frac{x_1}{r_{11}} \right)^3 \right] r_{11}^2 - \frac{1}{2} x_1 \sqrt{r_{11}^2 - x_1^2} = 2 \alpha_1 A_0 \Delta T + A_{01}
\]

All parameters except for \( r_{11} \) are either readily available or can be solved for. Therefore equation 3.38 has only \( r_{11} \) as the unknown. By using the Newton-Raphson Iterative Method the value of \( r_{11} \) can be calculated.

The following equations were used in the iteration process of determining \( r_{11} \):

\[
r_{11+1} = r_{11} - \frac{f(r_{11})}{f'(r_{11})}
\]

\[
f(r_{11}) = \left( \sigma_{01} - r_{11} + \sqrt{r_{11}^2 - x_1^2} \right) x_1 + \frac{1}{2} \left[ \frac{x_1}{r_{11}} + \frac{1}{6} \left( \frac{x_1}{r_{11}} \right)^3 \right] r_{11}^2 - \frac{1}{2} x_1 \sqrt{r_{11}^2 - x_1^2} - A_{01}(1 + 2 \alpha_1 \Delta T_1)
\]

By expanding and simplifying the above equation,

\[
f(r_{11}) = x_1 \sigma_{01} - \frac{x_1^2 r_{11}}{2} + \frac{x_1}{2} \sqrt{r_{11}^2 - x_1^2} + \frac{x_1^3}{12 r_{11}} - A_{01}(1 + 2 \alpha_1 \Delta T_1)
\]

The first derivative with respect to \( r_{11} \) of the above equation is

\[
f'(r_{11}) = \frac{x_1 r_{11}}{2 \sqrt{r_{11}^2 - x_1^2}} - \frac{x_1^3}{2} - \frac{x_1^3}{12 r_{11}^2}
\]
The iteration process starts by using $r_{01}$ as the initial value of $r_{11}$. Then this value is plugged into the above equations in order to obtain the new value of $r_{11}$. The computed value of $r_{11}$ is again plugged into the same equations in the next iteration. The process of iteration continues until the difference between the successive values of $r_{11}$ is negligible or smaller than what is specified.

**For Asperity 2**

Let

$A_{02} =$ the original area which is bounded as shown in figure 3.6 by the line $x_2$ and the circular arc of angle $\theta_{02}$

$A_{12} =$ the area after thermal expansion which is bounded as shown in figure 3.6 by the line $x_2$ and the circular arc of angle $\theta_{12}$

Then from figure 3.6,

$$A_{02} = \frac{1}{2} \theta_{02} r_{02}^2 - \frac{1}{2} x_2 r_{02} \cos \theta_{02} \quad 3.38$$

where:

$$x_2 = \frac{\sigma_{02}}{m_{02}}; \quad m_{02} = \text{rms slope}$$

$$\frac{\theta_{02}}{2} = \tan^{-1}(m_{02})$$

The area after expansion is

$$A_{12} = \frac{1}{2} \theta_{02} r_{12}^2 - \frac{1}{2} h x_2 \quad 3.39$$
Figure 3.6 Two Dimensional Thermal Expansion of Asperity 2
Solving for the area due to thermal expansion

\[ A_{12} - A_{02} = 2\alpha_2 A_{02} \Delta T_2 \]  
\[ = \text{one-half of the cross-hatched area of figure 3.6} \]

From figure 3.6

\[ \frac{\sqrt{r_{12}^2 - x_2^2}}{r_{12}} = \frac{h}{r_{12}} \]  
\[ \sin \theta_{12} = \frac{x_2}{r_{12}} \]

Solving for the angle \( \theta_{12} \) and then expressing it in a series form

\[ \theta_{12} = \sin^{-1}\left(\frac{x_2}{r_{12}}\right) = \frac{x_2}{r_{12}} + \frac{1}{6} \left(\frac{x_2}{r_{12}}\right)^3 + \frac{3}{40} \left(\frac{x_2}{r_{12}}\right)^5 \triangledown \]

For \( x_2 < r_{12} \) the third term of the above equation can be neglected resulting to

\[ \theta_{12} = \sin^{-1}\left(\frac{x_2}{r_{12}}\right) = \frac{x_2}{r_{12}} + \frac{1}{6} \left(\frac{x_2}{r_{12}}\right)^3 \]  
\[ \triangledown \]

Substituting equations 3.40, 3.41, 3.42 into equation 3.39 and rearranging, the resulting equation is

\[ \frac{1}{2} \left[ \frac{x_2}{r_{12}} + \frac{1}{6} \left(\frac{x_2}{r_{12}}\right)^3 \right] r_{12}^2 - \frac{1}{2} x_2 \sqrt{r_{12}^2 - x_2^2} = A_{02} + 2\alpha_2 A_{02} \Delta T_2 \]  
\[ \triangledown \]
All parameters except for \( r_{12} \) are either readily available or solvable. Therefore equation 3.43 has only \( r_{12} \) as the unknown. By using the same iterative method used for asperity 1 the value of \( r_{12} \) can be calculated.

3.3 Calculation of the Area of Contact of the Two Asperities with Spherical Tips

Two cases are considered here. One is without heating and the other is with heating. The Herztian equation for two contacting elastic spheres is the basis in the subsequent mathematical relationships.

**Without Heating**

From Timoshenko and Goodier (1951), the equation for the radius of the contact area of two spheres is

\[
\frac{3\pi}{4} \frac{P \left( \frac{1 - \nu_1^2}{\pi E_1} \right) + \left( \frac{1 - \nu_2^2}{\pi E_2} \right) r_{01} r_{02}}{r_{01} + r_{02}}
\]

By expanding and rearranging the above,

\[
a_0 = \left\{ \frac{3P E_2 \left( 1 - \nu_2^2 \right) + E_1 \left( 1 - \nu_1^2 \right)}{E_1 E_2} \right\}^{\frac{1}{3}} \frac{r_{01} r_{02}}{r_{01} + r_{02}}
\]

Therefore the area of contact if there is no heating is

\[
A_{\text{cont0}} = \pi a_0^2
\]

where \( a_0 \) is obtained using equation 3.44
With Heating

Using the same procedure applied to without heating, the radius of the area of contact of the two spheres subjected to thermal expansion is

\[ a_1 = \left\{ \frac{3P}{4} \frac{\left[ E_2 \left( 1 - v_1^2 \right) + E_1 \left( 1 - v_2^2 \right) \right]}{E_1 E_2} \frac{r_{11} r_{12}}{r_{11} + r_{12}} \right\} \frac{1}{3} \]  

3.46

The area of contact is therefore

\[ A_{\text{cont}_1} = \pi a_1^2 \]  

3.47

The ratio of the area of contact with heating to the area without heating is

\[ \frac{A_{\text{cont}_1}}{A_{\text{cont}_0}} = \left[ \frac{r_{11} r_{12} (r_{01} + r_{02})^2}{r_{01} r_{02} (r_{11} + r_{12})^3} \right] \]  

3.48

Equation 3.48 is incorporated into the thermal contact conductance equation as explained below:

The general form of the thermal contact conductance equation is given by

\[ h \frac{\sigma}{k} = f m^8 \left( \frac{P}{H} \right)^d \]
The effect of the change in the contact area of the two spheres as the heat flow is reversed is incorporated into the above equation as explained below.

From equation 3.12, \( P/H \) can be expressed in terms of the actual contact area and the nominal area, i.e.,

\[
\frac{A_r}{A} = \frac{P}{H}
\]

The above contact area, \( A_r \), however does not take into consideration the variation due to changes in temperature as a result of heat flow reversal. To account for this, the contact area with consideration of thermal expansion is obtained by multiplying both sides of the above equation by the ratio of the areas of contact. The result is

\[
\frac{A_r}{A} = \frac{P}{H} \frac{A}{A_{cont_0}}
\]

\( A_r \) is just equal to the contact area without heating, \( A_{cont_0} \). Therefore equation 3.49 becomes

\[
\frac{A_{cont_1}}{A} = \frac{P}{H} \frac{A}{A_{cont_0}}
\]

By incorporating equation 3.50 into the equation for thermal contact conductance the resulting expression is

\[
h = f \cdot m \cdot g \left( \frac{A_{cont_1}}{A_{cont_0}} \frac{P}{H} \right)^d
\]
The values of \( f \), \( g \), and \( d \) used in the calculation are 0.50, 1, and 0.95 respectively. The microhardness used is the smaller of the two microhardness values of the specimens. The slope, \( m \), and roughness, \( \sigma \) are square roots of the sum of squares of each slope and roughness of each contacting surface respectively. The thermal conductivity, \( k \), is the harmonic mean of the thermal conductivities of the contacting solids.

3.4 Description of the Computer Program for the Calculation of the Thermal Contact Conductance

A computer program was developed based on the model previously discussed. The calculation of the thermal contact conductance is based on equation 3.51. The program calculates the thermal contact conductance for both directions of heat flow. The heat flow process is represented by figure 1.1 of chapter 1.

Program Input

The inputs needed for the calculation process are a set of fixed inputs and a set of variable inputs.

A. Inputs that are fixed for a particular pair of contacting specimens

1. Roughness and slope of the contacting surfaces
2. Thermal conductivity of the each specimen expressed as a linear function of temperature
3. Surface microhardness of the specimen expressed as a function of the roughness and slope
4. Coefficient of linear thermal expansion

B. Input which can be varied

1. Heat Flux
2. Temperature, \( T_0 \)
3. Contact Pressure
Start

Input $\sigma_1$, $\sigma_2$, $m_1$, $m_2$, elasticity $E_1$ and $E_2$, initial value of $T_2$ and number of heat flow reversal $n$

Compute effective roughness, slope and elasticity

Input heat flux $q$, $T_0$ and contact pressure $P$

No. of iterations>30

Swapping already done

Print $h$

$h = h$ at the 30th iteration

Sequential computation of the following:
1) $T_1$
2) Radii of the contacting asperities (without heating)

Sequential computation of the following:
1) Radii of contacting asperities (with heating)
2) Harmonic mean of the thermal conductivities
3) Ratio of contact areas with heating and without heating
4) Microhardness of the softer material
5) Thermal contact conductance $h$

Recompute $T_2$
$T_2 = T_1 - q/h$

No. of iterations>30

Swapping already done

yes

Print contact pressure and heat flux

no

Swapping the top specimen to the bottom and the bottom specimen to the top does reversal of the heat flow direction

Print $h$

No. of reversals>n

End

Figure 3.7 Simplified Flow Chart of the Computer Program
3.5 Computer Program Output

A typical calculation using the computer program previously discussed is presented below. The data are obtained from one of the experiments performed.

Input values for the calculation

A. Fixed Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>roughness, μm</td>
<td>σ</td>
<td>1.804</td>
<td>5.508</td>
</tr>
<tr>
<td>slope</td>
<td>m</td>
<td>0.4607</td>
<td>0.6021</td>
</tr>
<tr>
<td>ther. conductivity</td>
<td>k</td>
<td>14.602 + 0.01232 T</td>
<td>14.602 + 0.01232 T</td>
</tr>
<tr>
<td>W/m-°C</td>
<td>α</td>
<td>0.0000174</td>
<td>0.0000174</td>
</tr>
<tr>
<td>coeff. of ther. exp., m/m-°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>microhardness, kPa</td>
<td>H</td>
<td>22922000(0.95σ/m)^0.6059</td>
<td>22922000(0.95σ/m)^0.6059</td>
</tr>
</tbody>
</table>

B. Variable Input

<table>
<thead>
<tr>
<th>Input No.</th>
<th>Heat Flux, W/m²</th>
<th>T₀, °C</th>
<th>Contact Pressure, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20421.81</td>
<td>175.2</td>
<td>196.5</td>
</tr>
<tr>
<td>2</td>
<td>22688.2</td>
<td>169.9</td>
<td>314.4</td>
</tr>
<tr>
<td>3</td>
<td>25458.6</td>
<td>165.1</td>
<td>786.0</td>
</tr>
<tr>
<td>4</td>
<td>29832.8</td>
<td>171.7</td>
<td>1375.4</td>
</tr>
<tr>
<td>5</td>
<td>31565.6</td>
<td>169.1</td>
<td>1964.9</td>
</tr>
<tr>
<td>6</td>
<td>33089.4</td>
<td>168.6</td>
<td>2554.4</td>
</tr>
<tr>
<td>7</td>
<td>33920.0</td>
<td>168.2</td>
<td>3143.9</td>
</tr>
<tr>
<td>8</td>
<td>34156.4</td>
<td>166.6</td>
<td>3733.3</td>
</tr>
<tr>
<td>9</td>
<td>35154.0</td>
<td>165.1</td>
<td>4440.7</td>
</tr>
</tbody>
</table>
Stability of the Iteration Process

Using the inputs enumerated earlier, the values of the radii of the asperities and the thermal contact conductance have stabilised after 5 iterations. Figures 3.8, 3.9, 3.10 and 3.11 show the calculated values with the number of iterations.

Figure 3.8 Iteration of the Radius of Asperity 1
Figure 3.9 Iteration of the Radius of Asperity 2
Figure 3.10 Iteration of the Thermal Contact Conductance at Low Contact Pressure

Figure 3.11 Iteration of the Thermal Contact Conductance at High Contact Pressure
Thermal Contact Conductance Output

The calculated thermal contact conductance against the contact pressure chart is shown in figure 3.12 below. It must be noted that the values were obtained using the fixed and variable inputs. Each value in the chart was derived by iteration. The number of iterations used for each is 30. This assured that the calculation had definitely stabilised.

![Conductance - Pressure Chart](image)

Fig. 3.12 Conductance vs Contact Pressure Curves of Both Directions of Heat Flow

Using equation 3.27 the radii of the asperity tips of specimens 1 and 2 are 5.152 and 10.35 \( \mu \text{m} \) respectively. From the above figure, an increase in thermal contact conductance (positive thermal rectification) occurs when the heat flow direction is from specimen 1 to specimen 2. For similar materials the positive thermal rectification occurs if the heat flows from a specimen with smaller radius to a specimen with a larger radius of asperity. This is to be validated in the experiments to be discussed in chapter 6.
CHAPTER 4
DESIGN, FABRICATION AND TESTING OF THE APPARATUS

As noted the mechanism of heat transfer across an interface depends on many different variables. The most important of them appear to be: 1) surface roughness; 2) surface flatness; 3) properties of the materials in contact; 4) mean interface temperature; 5) heat flux across the interface; and 6) contact pressure. In an experimental investigation, the first three variables are usually determined using conventional apparatus for surface measurement and materials testing such as surface analyser and a microhardness tester. The last three variables are usually obtained simultaneously in an apparatus for thermal contact conductance experiment. An axial heat flow cut bar type of apparatus is commonly used for thermal contact conductance experiments.

4.1 Design of the Apparatus

The apparatus was designed in such a manner as to have control on the following parameters:

(a) Heat Input

The thermal contact conductance is equal to the heat input divided by the temperature drop across the joint. The apparatus must have the capability of obtaining the heat input and the temperature drop across the contact in order to be able to compute the thermal contact conductance. Aside from that it must be capable of varying the heat input.

(b) Direction of Heat Flow

The thermal contact conductance may increase or decrease depending on the direction of heat flow. The apparatus must be capable of performing experiments on the dependency of thermal contact conductance on the direction of heat flow. To achieve this, it must be able to reverse the direction of heat flow with the important
condition that the contacting specimens are not disturbed during the reversal process.

(c) Contact Pressure

The thermal contact conductance is highly dependent on contact pressure. The apparatus must have a provision for varying the contact pressure in order to accurately measure the dependency of contact conductance on contact pressure.

(d) Vacuum Environment

It should be possible to conduct tests in vacuum so that the solid spot conductance can be isolated.

(e) Introduction of Specified Gas Into the Vacuum Chamber

Most gases have temperature dependent thermal conductivities. The apparatus must have a provision for introducing gas into the vacuum chamber so that experiments on the behaviour of thermal contact conductance with the presence of gas in the chamber and for different directions of heat flow can be performed.

The above requirements were all considered in deciding on the design of the following features and major parts of the apparatus:

(1) Vacuum Chamber

The vacuum chamber has a 120mm outside diameter, 80-mm height an is made of 7mm thick pyrex glass. Glass was chosen so that the inside assembly could be viewed at any time especially during the start-up. The volume of the chamber is kept to a minimum so that it would not take too long to obtain the desired vacuum. The degassing problem is also minimised since the chamber is made of glass. The top and bottom covers of the vacuum chamber were machined from a 16-mm thick stainless steel plate. The covers have holes to locate the heat flux meters and test specimens assembly, thermocouple wires, vacuum pump line, and inert gas line. Each cover has a groove for the O – ring. The groove has an epoxy lining. The purpose of the epoxy
lining is to make sure that the glass vacuum chamber sits on the epoxy lining and O-ring and not on the stainless cover (Figure 4.1). This will prevent scratching the edge of the pyrex glass vacuum chamber.

![Figure 4.1 Glass Chamber and Stainless Steel Cover O-ring Assembly](image)

(2) Vacuum Pump

The vacuum pump used is a LEYBOLD TRIVAC D1.6B dual-stage pump. It is oil-sealed rotary vane pump. It can pump gases and vapours and evacuate vessels or vacuum systems in the medium vacuum range (0.100-0.001 mbar).

(2) Vacuum Pressure Gauge

The instrument for measuring the vacuum pressure is a THERMOVAC TM 20 gauge. It can measure vacuum pressure within the range between 0.001 mbar and atmospheric pressure. It is a thermal conductivity gauge that utilise the thermal conductivity of
gases inside the vacuum chamber for the measurement of the vacuum pressure (Pirani principle).

Thermal conductivity gauges are based on a filament mounted in a glass or metal envelope attached to the vacuum system (Roth, 1990). The filament is heated by the passage of an electric current. The temperature of the filament depends on the rate of supply of electrical energy, the heat loss by conductivity through the surrounding gas, the heat loss due to radiation and convection, and the heat loss through the support leads to the filament. For a specific range of pressure (0.100-.0001 mbar) the temperature of the wire depends primarily on the loss of energy due to thermal conductivity of the gas if the rate of supply of electrical energy is maintained constant, and the radiation plus support lead losses are minimised. The loss of energy due to the thermal conductivity of the gas is a direct function of the pressure. The temperature variations of the filament with pressure are measured in terms of the change of the resistance.

(3) Reversible Direction of Heat Flow

The apparatus has heater and cooling systems on either end of the column assembly. The heater and cooling systems operate one at a time, i.e., for heat flow from top to bottom, the upper heater and the lower cooler are used and vice versa if the direction of heat flow is reversed. Both the heaters and the coolers are placed outside the vacuum chamber. This arrangement differs from the conventional apparatus in which they are located inside the vacuum chamber. The main advantages of this arrangement are the following:

a) Possibility of leakage in the vacuum chamber is minimised because there are fewer openings into the chamber;

b) Better maneuverability inside the vacuum chamber;

because only the thermocouple wires, specimens, and heat flux meters are occupying the vacuum chamber. This was found to be of great advantage when the experiments with
inert gases were performed. In the experiments the heat flux meters and test specimens were insulated to minimise the radial flow of heat. The fabrication and installation of the insulators were relatively not difficult.

c) Ordinary types of heater can be used;

It must be noted that many commercially available heaters are not guaranteed to work under vacuum. The heater installed in the apparatus is an 80-watt clamped-type electric heater. The heating is controlled by a VARIAC that is connected in between the heater and the electric power source.

d) Possibility of the cooling medium leaking into the vacuum chamber is eliminated.

The cooling medium used is water that circulates through the cooling system of the apparatus and a chiller. The chiller is a conventional one with a thermostat for setting the temperature of the cooling medium. Since the cooling system of the apparatus is outside the vacuum chamber the possibility of water leaking into it is completely eliminated.

5) Variable Contact Pressure

The interface contact pressure is made variable by a deadweight and lever system. The lever ratio is 6:1. With a set of weights, the contact pressure can be varied within the range from 100 kPa to 5 MPa.

6) Provision to Accommodate Inert Gas into the Vacuum Chamber

The apparatus has a gas line with a valve that can control the inlet flow into the vacuum chamber. Any desired gas can then be introduced into the chamber enabling test to be conducted in different gas environments. Note that the pressure of the introduced gas inside the chamber should be slightly higher than atmospheric. The positive pressure ensures that the gas in the chamber is not contaminated by atmospheric air.
7) Two Heat Flux Meters

The apparatus has two heat flux meters that are placed at the ends of the test specimens assembly. They are for measuring the heat flux accurately. They are cylindrical in shape with a diameter of 18mm and length of 25mm. Each has three holes of 1mm diameter and 9mm depth; to accommodate the thermocouple wires. Figure 4.2 shows the dimensions and shape of the heat flux meter. Any type of metal can be used as heat flux meter as long as its thermal conductivity is known accurately and can withstand the heating and compressive load applied on it. In the present case the material for the heat flux meter is RM 8421. It is an electrolytic iron with a purity of 99.90 % by weight and density of 7.867 ± 0.005 g/cm³. It was obtained from the National Institute of Standards and Technology of the United States of America who also supplied the thermal conductivity data of the reference material.

![Figure 4.2 Details of the Heat Flux Meter](image)

NOTES:
1) All dimensions are in millimetres
2) Drawn not to scale

Figure 4.2 Details of the Heat Flux Meter
Table 4.1 shows the thermal conductivity and electrical resistivity properties as a function of temperature from 2 to 1000K of the heat flux meter material. The estimated uncertainties of the thermal conductivity data are 2% below and 3% above 280K. The recommended values are corrected for thermal expansion. A plot of thermal conductivity versus temperature is shown in Figure 4.3.

<table>
<thead>
<tr>
<th>T(K)</th>
<th>K(Wm⁻¹K⁻¹)</th>
<th>ρ(nΩm)</th>
<th>T(K)</th>
<th>K(Wm⁻¹K⁻¹)</th>
<th>ρ(nΩm)</th>
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Table 4.1 Thermal Conductivity and Electrical Resistivity as Functions of Temperature of the Heat Flux Material (RM 8421).
Figure 4.3 Thermal Conductivity as Function of Temperature of the Heat Flux Material (RM 8421).

From figure 4.3, an equation relating the thermal conductivity with the temperature was obtained. A curve fitting within the range of 200 to 1000 K was done. The temperature range used is the range of which the experiments were performed. Figure 4.4 presents the curve and the corresponding equation for the thermal conductivity is

\[
k = 109.96e^{-0.0012T}
\]

where:

\[
k = \text{thermal conductivity, W/(mK)}
\]
\[
T = \text{temperature, K}
\]
The correlation between the actual and the computed values using the equation within the range of 200 to 1000 K is excellent and the error is very small.

<table>
<thead>
<tr>
<th>T(K)</th>
<th>k (actual)</th>
<th>k(solved)</th>
<th>error(%)</th>
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correlation = 0.999938

Figure 4.4 Thermal Conductivity Equation of RM 8421 material

The heat flux flowing through the cross-section of the specimens is determined according to the Fourier's law of heat conduction. It is shown below in equation form for one-dimensional heat flow.

\[ q = -k \frac{dT}{dx} \] (4.2)

Plugging equation 4.1 into equation 4.2 and then integrating from \( T_1 \) to \( T_2 \) yields the following result:
\[ q = \frac{109.96}{0.0012x} \left( e^{-0.0012T_2} - e^{-0.0012T_1} \right) \quad 4.3 \]

where:
- \( q \) = heat flux, W/m²
- \( x \) = distance between temperature reading points, m
- \( T_1, T_2 \) = temperature readings, K

8) Two Test Specimens
The test specimens have a shape that is similar to the heat flux meter (Figure 4.2). A detailed description of the specimens is presented in Chapter 5.

9) Thermocouple Wires
The thermocouple wire type used is Teflon insulated, 36 AWG, type K (TW-K36-c/c). The insulation can withstand a maximum temperature of 260 °C. The wire diameter is 0.08 mm. The thermocouple junctions were made by welding the wires using the capacitor bank discharge method.

10) Data Acquisition System
The data acquisition set-up is composed of two 8-channel ADAM-4018 Analog/Thermocouple Input Modules, one ADAM RS-232 to RS-422/RS-485 converter, one power supply and a computer. Computer programs for data gathering and processing were generated. They are written in QuickBasic computer language. Figure 4.5 shows the schematic diagram of the data acquisition set-up.
Figure 4.5 Schematic Diagram of the Data Acquisition System
4.2 Fabrication of the Components of the Apparatus

The fabrication of the components of the apparatus was done in the machine shop of the School of Mechanical and Manufacturing Engineering of the University of New South Wales. Materials, parts and accessories were acquired locally or within Australia except for the heat flux meter material. The pyrex glass chamber was cut and polished by the supplier.

4.3 Installation and Testing of the Apparatus

The installation of components and accessories was straightforward since the dimensions were according to standards. The installation of the thermocouple wires however needs to be specially mentioned because their introduction into the vacuum chamber posed the highest possibility of occurrence of a leakage. The thermocouples passed through a U – tube (see Figure 4.6) into which A PIEZON wax was poured for sealing. The sealing of the U – tube had to be properly and carefully done as will be explained later in this section.

![Figure 4.6 Schematic Diagram of the Sealing of the U - tube](image)
The following were done in the sealing of the U-tube:

1) Stripping of the transparent insulation

Figure 4.7 illustrates the cross-section of the thermocouple. There are two wires, each of which is insulated, separately and then the pair is covered with an additional transparent insulation.

![Figure 4.7 Schematic Diagram of the Cross Section of the Thermocouple](image)

It was found out that if the thermocouples were inserted as received through the U-tube and sealed with APIEZON wax, there was a leak at the end of some thermocouples. The leaks were detected by injecting compressed air into the vacuum chamber and placing the vacuum chamber and thermocouple under water. Bubbles were observed indicating that air passed through the interior of the thermocouple. The source of the leak is indicated in the figure. The leak was eliminated by stripping out the transparent insulation before sealing it with the wax. Only the part where the thermocouple was sealed with the wax was stripped. In the stripping process, great care was taken not to slice the wire insulation. The best way of doing this was to slice with slight pressure using a sharp blade in between the
wire and moving along the length. Then the transparent insulation could be easily pulled out and cut.

2) Sealing by Using the APIEZON Wax

The wax was melted in a beaker (melting temperature is around 100°C). The U–tube where the thermocouples passed through was heated evenly. When the U–tube was hot enough (around 90°C), the molten wax was poured into the tube. From time to time the pouring of the wax was stopped for a while and then the thermocouples were pulled back and forth (length of each stroke is approximately 30cm.) while the heating of the tube continued. This ensured that trapped air bubbles were allowed to escape.

Figure 4.8 shows the schematic diagram of the apparatus minus the accessories and the data acquisition system that was previously explained with reference to figure 4.4. A thorough testing of the experimental apparatus was done after the elimination of leaks. The objective of the tests was to check the performance of the following features when operated simultaneously:

1) vacuum pump;
2) chiller;
3) electric heater;
4) vacuum pressure gauge;
5) data acquisition set–up;
6) vacuum chamber;
7) variable voltage input for the heater;
8) variable contact pressure; and
9) circulation of cooling water.
Figure 4.8 Diagram of the Experimental Apparatus
The operating conditions of the apparatus are:

(1) Maximum temperature of 230°C – this is due to the temperature limitations of the O-ring.
(2) Maximum contact pressure of 5.0 MPa – the deadweight lever set-up was designed for this contact pressure.
(3) Highest vacuum it can attain is in the order of $10^{-2}$ mbar.

Figures 4.9a and 4.9b are pictures of the experimental apparatus and its accessories. In figure 4.9a, the following can be seen:

1) Vacuum pump and chiller located below the table
2) Two ADAM data acquisition modules and one ADAM converter at the top of the table
3) Vacuum pressure gauge head and valve along the vacuum pump to vacuum chamber line
4) VARIAC at the back of the computer
5) Experimental apparatus showing the insulation inside the chamber

Figure 4.9b shows the following:

1) Provision for introducing gas into the vacuum chamber
2) Pressure gauge and valve along the gas line
3) Vacuum pressure display monitor at the side of the computer
4) Experimental apparatus showing the lever for contact pressure variation
Figure 4.9 Pictures of the Experimental Apparatus and Its Accessories
4.4. Calibration of the Apparatus

The calibration was done after it was established that all components of the apparatus were working well. It was centred on the contact pressure and temperature readings.

a) Contact Pressure

The net tare weight of the lever was obtained. The net tare weight is the value after considering the weight of the lever and the spring action of the flexible (corrugated) tubing. By considering also the effect of the vacuum on the contact pressure the following equation was obtained:

\[
P_{\text{contact}} = 23.579 \, W - 0.10866 \, P_{\text{vacuum}} + 196.49
\]

where:

- \( P_{\text{contact}} \) = contact pressure, kPa
- \( W \) = dead weight, Newton
- \( P_{\text{vacuum}} \) = vacuum pressure, mbar

In the above derivation, it is noted that the specimen diameter is 18 mm.

b) Temperature Readings

The thermocouples were calibrated by placing them in an oil bath with a heater. A temperature probe of a RTD Digital Thermometer (Fluke 2180A) was placed very near the thermocouples. The correctness of the RTD probe readings was verified first before using it for the calibration. The verification was done at ice and boiling points of water using a procedure recommended by the manual supplied with the probe. The accuracy of the RTD is ± 0.098°C at a resolution of 0.01°C. At different temperatures, the readings of the thermocouples was plotted against the readings of the probe. A typical plot is shown...
in figure 4.10. The figure refers to the calibration of thermocouple no. 010. An equation was obtained from the plot. The equation was then used in calculating the calibrated temperature.

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\[ y = 0.9991x + 1.1428 \]
\[ R^2 = 1 \]

CORRELATION = 0.999995

Figure 4.10 Typical Thermocouple Calibration Plot

Typical result of an experimental run is presented in figure 4.11. Table 4.2 shows results for a contact heat transfer experiment. The negative signs
Figure 4.11 Typical Results of an Experimental Run
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<th>Experiment No.</th>
<th>qflux(top) (watt/sq.m)</th>
<th>qflux(bott) (watt/sq.m)</th>
<th>qflux(aver) (watt/sq.m)</th>
<th>delta T (K)</th>
<th>hconduct (Watt/sq.m·K)</th>
<th>mean T (K)</th>
<th>contPress (kPa)</th>
<th>Direction of heat flow</th>
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**Table 4.2 Typical Results of a Contact Heat Transfer Experiment**
for the heat flux indicate that its heat flow direction was reversed. In some cases the heat flux measurements of the two heat flux meters differ from each other. The difference is usually less than 4 % of the average of the two. The difference can be attributed to the error due to the off-centre location of the thermocouple wire junctions inside the holes. There is always a possibility that the thermocouple wire junctions are off-centred because of the clearance between the wire junction and the hole. The clearance depends on the diameter of the wire junction. The size of the wire junction can not be easily controlled since it depends on the result of welding of the thermocouple wire. In the average the clearance is approximately equal to 0.30mm. An error occurs because the distance between thermocouple wires used in the linearisation and calculation is the centre to centre distance of the holes and not the actual distance between thermocouple wire junctions. Appendix B presents the values of the error and uncertainties in the calculation of the heat flux and thermal contact conductance due to this off-centre location of wire junctions in the holes. Note that in the uncertainty calculation the most detrimental situation was considered in the determination of primary measurements. The possibility that all of the worst situations in the primary measurements will occur at the same time is very unlikely.

The thermocouples were installed in the temperature holes by inserting them first in short small stainless steel tubes. Length and outside diameter of the tube are approximately 1.2 and 1.0 millimetres respectively. One end of the tube was then pressed in order to clamp the thermocouple wires. The tube acted as a lock to keep the thermocouple wires in place. Then a small amount of epoxy was applied to make sure that the thermocouple did not move during the installation of the heat flux metres and test specimens assembly. Although heat transfer fluid/paste could be used it was found out that the improvement in the measurement was not significant and was offset by the following disadvantages:

1) Some heat transfer paste/fluid disintegrate at higher temperature.
2) If the paste is used the thermocouple can be used only once. It has to be re-welded and re-calibrated every time a new pair of specimens is used.

3) Evacuation of the vacuum chamber takes more time because of the degassing of the paste/fluid.

Maximum heat loss due to radiation was calculated to be approximately 1.4 % (See Appendix C). Other losses were not considered critical because the heat losses, e.g., from the heater, were outside the vacuum chamber and did not affect the experimental results.
CHAPTER 5
GENERAL METHODS AND MATERIALS

The three areas on thermal contact conductance considered in this work are the following:

1) thermal rectification (directional effect) of similar and dissimilar metals under vacuum;
2) effect of interstitial materials (metallic foils) on thermal contact conductance; and
3) directional effect on gas gap conductance

They were performed using different experimental procedures. However, there were methods and materials, which were common to all of them. They were the following:

1) Test specimens and their preparation
2) Determination of mechanical and thermal properties of the specimen

5.1 Test Specimens and Their Preparation

All specimens were machined to the shape and dimension as shown in figure 4.2 of chapter 4. Three kinds of materials were used. They were stainless steel (SS 304), aluminium (Al 6060), and NILO 36. Unlike the stainless steel and aluminium materials, NILO 36 is a special type of metal. It is a binary nickel-iron alloy with 36% Nickel and 64% Iron nominal composition. It is used in precision engineering applications because of its very low coefficient of thermal expansion (approximately one-tenth of that of stainless steel). The specimens were machined from a single bar stock for each material type, ensuring that the properties of the specimens were similar for a particular type of material. The end surfaces of each specimen were ground flat by hand polishing. They were then mirror-finished (rms roughness \(\approx 0.3 \ \mu m\)) by a flat diamond grit surface polisher. After surface polishing the ends were cleaned using ethanol in preparation for surface blasting.
The process of making the surface rough is by blasting the specimen with abrasive. Before the blasting operation each specimen was wrapped with masking tape with the end surfaces exposed. Then the specimens that would be subjected to the same type of abrasive and blasting pressure are bunched together with masking tape. This ensured that the specimens were stable during the blasting process. Three types of abrasives were used. They were 1) garnet, 2) aluminium oxide, and 3) glass beads. The roughness of the blasted surface depended on the following factors:

a) Grit size – this is usually expressed in terms of the mesh number; and the lower the mesh number, i.e., the larger the particle size, the rougher is the resulting blasted surface.

b) Blasting pressure – the higher the blasting pressure the rougher is the surface.

Impact Glass Beading Company, Blacktown, New South Wales carried out the blasting. Figure 5.1 shows an illustration of the blasting process. After the blasting process the surfaces were cleaned with ethanol and were set for the surface analysis. The surface parameters needed for the theoretical analysis were the root-mean-square (rms) slope and the rms roughness of the surface profile. The surface analysis of the first batch of test specimens was performed at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) at Lindfield, New South Wales, Australia. The equipment used was a Talysurf 5 surface roughness analyser. The results of the analysis are shown in Table 5.1. The values of the slope and the roughness were the average of three to seven measurements in different spots of the surface. The first three measurements were observed and if the variations of readings were higher than 5% further measurements were done. Too many measurements were avoided because the stylus of the apparatus scratched the surface in every measurement and might affect the surface profile. Those specimens with more than 20% variations of measurement were rejected. The N, S, and A letters for the specimen number represent NILO 36, SS 304 and Aluminium 6060 materials respectively.
Abrasive and air mixture at high pressure

Figure 5.1 Blasting Process Schematic Diagram
<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Abrasive</th>
<th>Blasting pressure, kPa</th>
<th>rms slope, radians</th>
<th>rms roughness, μm</th>
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</thead>
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<td>2.5680</td>
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<td>0.3850</td>
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Table 5.1 Results of Surface Analysis Done at CSIRO
The other batch of test specimens was analysed at the Precision Laboratory of the School of Mechanical and Manufacturing Engineering of the University of New South Wales (UNSW). The equipment used was Talysurf 4 surface analyser interfaced with a personal computer with software especially written for the purpose of processing the data. Before doing the roughness analysis, standard surfaces with known surface characteristics were used to check the accuracy of the equipment. Some specimens that were analysed at CSIRO were crosschecked and the results were found to be similar. Table 5.2 presents the results of the surface analysis.

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<th>Specimen No.</th>
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<th>rms roughness, μm</th>
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<td>S11</td>
<td>Al oxide, size 80</td>
<td>550</td>
<td>0.5983</td>
<td>3.5507</td>
</tr>
<tr>
<td>N7A</td>
<td>Al oxide, size 80</td>
<td>550</td>
<td>0.6163</td>
<td>4.7128</td>
</tr>
<tr>
<td>N9A</td>
<td>Al oxide, size 80</td>
<td>550</td>
<td>0.6775</td>
<td>4.2313</td>
</tr>
<tr>
<td>N10A</td>
<td>Al oxide, size 80</td>
<td>550</td>
<td>0.6207</td>
<td>3.8970</td>
</tr>
<tr>
<td>N12X</td>
<td>Al oxide, size 80</td>
<td>550</td>
<td>0.5889</td>
<td>3.4944</td>
</tr>
<tr>
<td>N11A</td>
<td>Al oxide, size 80</td>
<td>550</td>
<td>0.6074</td>
<td>3.9214</td>
</tr>
<tr>
<td>S6X</td>
<td>Al oxide, size 80</td>
<td>200</td>
<td>0.4607</td>
<td>1.8040</td>
</tr>
<tr>
<td>A6A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5203</td>
<td>2.9569</td>
</tr>
<tr>
<td>A9A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5312</td>
<td>3.1070</td>
</tr>
<tr>
<td>A8A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5271</td>
<td>3.2534</td>
</tr>
<tr>
<td>A7A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5160</td>
<td>2.9432</td>
</tr>
<tr>
<td>A3A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5545</td>
<td>3.1378</td>
</tr>
<tr>
<td>A1A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5461</td>
<td>3.6770</td>
</tr>
<tr>
<td>A5A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5521</td>
<td>3.3192</td>
</tr>
<tr>
<td>A2A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5380</td>
<td>3.1695</td>
</tr>
<tr>
<td>A10A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5193</td>
<td>3.1729</td>
</tr>
<tr>
<td>A4A</td>
<td>Glass beads, 90-45µm</td>
<td>500</td>
<td>0.5286</td>
<td>3.1507</td>
</tr>
<tr>
<td>A24</td>
<td>Glass beads, 90-45µm</td>
<td>250</td>
<td>0.4887</td>
<td>2.6610</td>
</tr>
<tr>
<td>A21</td>
<td>Glass beads, 90-45µm</td>
<td>250</td>
<td>0.4859</td>
<td>2.8004</td>
</tr>
<tr>
<td>A23</td>
<td>Glass beads, 90-45µm</td>
<td>250</td>
<td>0.4988</td>
<td>2.6469</td>
</tr>
<tr>
<td>A25</td>
<td>Glass beads, 90-45µm</td>
<td>250</td>
<td>0.4976</td>
<td>2.6561</td>
</tr>
<tr>
<td>A22</td>
<td>Glass beads, 90-45µm</td>
<td>250</td>
<td>0.4999</td>
<td>2.7484</td>
</tr>
<tr>
<td>A20</td>
<td>Glass beads, 90-45µm</td>
<td>250</td>
<td>0.4946</td>
<td>2.8077</td>
</tr>
<tr>
<td>A26</td>
<td>Glass beads, 90-45µm</td>
<td>250</td>
<td>0.4888</td>
<td>2.5643</td>
</tr>
<tr>
<td>A13</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4810</td>
<td>2.2231</td>
</tr>
<tr>
<td>A18</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4422</td>
<td>2.1928</td>
</tr>
<tr>
<td>A15</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4975</td>
<td>2.2139</td>
</tr>
<tr>
<td>A11</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4713</td>
<td>1.9828</td>
</tr>
<tr>
<td>A14</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4864</td>
<td>2.2474</td>
</tr>
<tr>
<td>A16</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4648</td>
<td>2.1351</td>
</tr>
<tr>
<td>A12</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4769</td>
<td>1.9719</td>
</tr>
<tr>
<td>A17</td>
<td>Glass beads, 90-45µm</td>
<td>100</td>
<td>0.4852</td>
<td>2.0222</td>
</tr>
<tr>
<td>A21X</td>
<td>Smooth finish</td>
<td>NA</td>
<td>0.3959</td>
<td>0.7864</td>
</tr>
<tr>
<td>A12A</td>
<td>Smooth finish</td>
<td>NA</td>
<td>0.4023</td>
<td>0.5669</td>
</tr>
<tr>
<td>S13A</td>
<td>Smooth finish</td>
<td>NA</td>
<td>0.3850</td>
<td>0.6368</td>
</tr>
<tr>
<td>S14X</td>
<td>Smooth finish</td>
<td>NA</td>
<td>0.3742</td>
<td>0.5562</td>
</tr>
<tr>
<td>A27</td>
<td>Smooth finish</td>
<td>NA</td>
<td>0.3968</td>
<td>0.5336</td>
</tr>
</tbody>
</table>

Table 5.2 Results of Surface Analysis Done at UNSW
5.2 Determination of the Mechanical and Thermal Properties of the Test Specimens

The mechanical and thermal properties of the test specimens that were of most importance to the study are:

1) Thermal properties
   a) thermal conductivity
   b) linear coefficient of thermal expansion

2) Microhardness

Standard handbook on metals and materials provided the mechanical and thermal properties of the test specimens. Publications from manufacturers and suppliers also furnished relevant data.

5.2.1 Thermal Properties

A plot of thermal conductivity against temperature of SS 304 obtained from a publication of 1966 International Nickel Limited is presented in figure 5.2. The American Society of Metals handbook (1985) provided the following values of thermal conductivity of SS 304: 16.2 and 21.5 W/mK at 100 and 500°C respectively. These values agree well with the figure.

Hegazy (1985) performed a linear regression on the thermal conductivity data as function of the temperature data of SS 304 at the end of a particular test series and obtained the following equation:

\[ k = 17.02 + 1.52 \times 10^{-2} T \]

where \( k \) and \( T \) are in W/m°C and °C respectively.

According to him the above equation was accurate to within ± 3% in the range of 60 to 250°C. He mentioned that the expression would yield higher values than those reported in the literature and that it was independently confirmed.
for the same bar stock specimens by another researcher (Fisher (1985)), in
the same laboratory as Hegazy.

Figure 5.2 Thermal Conductivity vs. Temperature Plot of SS 304
The above discussion illustrates that thermal conductivity may differ even if it refers to the same type of material. The actual thermal conductivities of the test specimens are determined by linear regression of the experimental data. It is based on the expression derived below.

Using the one-dimensional heat conduction equation, \( q = -kdT/dx \) and expressing \( k = \alpha + \beta T \), the following equation is obtained after integrating from thermocouple locations 1 to 2:

\[
-q(x_2 - x_1) = \left[ \alpha + \beta \left( \frac{T_2 + T_1}{2} \right) \right] (T_2 - T_1)
\]

5.1

If we let \( T_{\text{aver}} = \left( \frac{T_2 + T_1}{2} \right) \), and \( k = \alpha + \beta T_{\text{aver}} \) then equation 5.1 becomes

\[
-q(x_2 - x_1) = k( T_2 - T_1 )
\]

5.2

From experimental data the thermal conductivity, \( k \) and \( T_{\text{aver}} \) are determined and plotted. The heat flux, \( q \) was determined using the heat flux meter made of standard reference material. A linear regression of \( k \) and \( T_{\text{aver}} \) will then result to an equation in the form \( k = \alpha + \beta T \).

After conducting the experiments the equation for the thermal conductivity of SS 304 was obtained by using the above process. The resulting expression is

\[
k = 14.602 + 0.01232 T
\]

5.3

where \( k \) and \( T \) are in W/m\(^{-}\)°C and °C respectively.

The above equation is plotted and compared with figure 5.2. This is shown in figure 5.3. It can be observed that the values obtained from equation 5.3 are slightly lower within the range of 100 to 600°C. Below 0°C they differ considerably. This indicates that a linear equation for the thermal conductivity of SS 304 is very accurate only over a short temperature range.
For NILO 36 the equation derived is

\[
k = 14.066 + 0.00553 T
\]

NILO 36 is a material that is not as common as SS 304. Its thermal conductivity as obtained from a publication by Henry Wiggin and Company Limited, a supplier of NILO series, is 0.025 cal/cm-sec-°C (10.47 W/mK) at 20°C. This is lower than the value obtained by using equation 5.4. Unfortunately there is no additional reference that can be cited. Values obtained by using equation 5.4 were the ones used in the numerical calculation.
For Al 6060 the equation obtained from the experiments is

\[ K = 179.17 + 0.2983 \, T \]

Its thermal conductivity as obtained from the ASM handbook is 180 W/m·°C at 25°C. This is close to the value obtained using equation 5.5.

The coefficient of linear expansion of SS 304 as function of temperature was obtained from the ASM handbook (1985). The values are tabulated below.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>From 0°C to</th>
<th>100°C</th>
<th>315°C</th>
<th>538°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean coeff. of thermal expansion, μm/m·°C</td>
<td>17.2</td>
<td>17.8</td>
<td>18.4</td>
<td></td>
</tr>
</tbody>
</table>

From the publication of Henry Wiggin and Company Limited, the mean coefficients of linear thermal expansion in millionths per deg °C of NILO 36 are:

<table>
<thead>
<tr>
<th>Temperature range, °C</th>
<th>20-100</th>
<th>20-200</th>
<th>20-300</th>
<th>20-400</th>
<th>20-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean coeff. of expansion</td>
<td>1.5</td>
<td>2.6</td>
<td>5.5</td>
<td>8.4</td>
<td>10.1</td>
</tr>
</tbody>
</table>

For Al 6060 from the ASM handbook, the coefficient of linear thermal expansion at 20 to 100°C is 23.6 μm.
5.2.2 Microhardness

The microhardness determination of the test specimens was conducted after using them in the experiments. The reason is that microhardness testing is a destructive process, although to a minute degree. The mounting and setting of the specimen, however, might cause alterations on the surface. The assumption is that the experimental process does not considerably affect the microhardness.

The microhardness of the surface of the specimen used for the contact was obtained by correlating the Vickers microhardness of the other end of the specimen, which was smooth. The microhardness measurement of actual rough surface using the conventional microhardness tester was very difficult to perform. This was because the indentation on the rough surface by the pyramid diamond indenter could not be clearly seen in the microscope. With the size of the indentation of the same order of the roughness, it was impossible to identify and measure the correct diagonal length of the indentation. To overcome this difficulty an expression relating the Vickers microhardness to the indentation was used. In a log-log scale the plot of the microhardness of metals against the indentation was a straight line and could be expressed by the following equation:

\[ H_v = c_1 d_v^{c_2} \]  

where:

- \( H_v \) = Vickers microhardness in GPa
- \( d_v \) = Vickers indentation diagonal in \( \mu m \)
- \( c_1 \) = Vickers microhardness when \( d_v = 1 \mu m \)
- \( c_2 \) = a negative exponent
Hegazy (1985) had related the Vickers indentation diagonal with the slope, $m$ and roughness, $\sigma$ of the surface in order to obtain the contact microhardness. The relation between the Vickers indentation diagonal, $d_v$, the slope, $m$, and roughness, $\sigma$ based upon equal indentation areas for a set of micro contacts is given by:

$$d_v = 0.95 \left( \frac{\sigma}{m} \right)$$  \hspace{1cm} 5.7

Substituting equation 5.7 into equation 5.6 results in

$$H_c = c_1 \left( \frac{0.95\sigma}{m} \right)^{c_2}$$  \hspace{1cm} 5.8

which is the equation for the contact microhardness where $\sigma$ is in $\mu$m. The correlation coefficients, $c_1$ and $c_2$ must be determined from the Vickers microhardness measurements of the softer surface.

Plots of the microhardness against the indentation of SS 304, NILO 36 and Al 6060 are shown in figures 5.4 and 5.5 below. Note that for Al 6060 the Vickers microhardness is in terms of MPa whereas for stainless steel SS 304 and NILO 36 it is in terms of GPa.
Microhardness of SS 304 and NILO 36

Figure 5.4 Microhardness vs. Indentation of SS 304 and NILO 36
Figure 5.5 Microhardness vs. Indentation of Al 6060
The values of $c_1$ and $c_2$ can be obtained by taking the logarithm of equation 5.6 as given below:

$$\ln H_v = c_2 \ln d_2 + \ln c_1$$  \hspace{1cm} (5.9)

Then the values obtained from equation 5.9 are plotted. A linear regression of the values would then yield an equation that is of the same form as equation 5.9. Figures 5.6 and 5.7 give the plots for SS 304, NILO 36 and Al 6060 using the natural logarithm of the microhardness and indentation values.

Microhardness of SS 304 and NILO 36

![Microhardness Graph](image)

Figure 5.6 Plot of the Logarithmic Values of Microhardness and Indentation of SS304 and NILO 36
Figure 5.7 Plot of the Logarithmic Values of Microhardness and Indentation of Al 6060
From the above figures, $c_1$ and $c_2$ can be determined as illustrated by the following:

**SS 304**

$\ln c_1 = 2.252$

$c_1 = 9.507$

$c_2 = -0.3738$

Therefore the Vickers microhardness equation for SS 304 is

$$H_v = 9.507d_v^{0.3738} \quad 5.10$$

**NILO 36**

$\ln c_1 = 1.3499$

$c_1 = 3.857$

$c_2 = 0.1635$

Therefore the Vickers microhardness equation for NILO 36 is

$$H_v = 3.857d_v^{0.1635} \quad 5.11$$

**Al 6060**

$\ln c_1 = 6.8438$

$c_1 = 938.05$

$c_2 = -0.0791$

Therefore the Vickers microhardness in terms of GPa for Al 6060 is

$$H_v = 0.938d_v^{0.0791} \quad 5.12$$
With \( c_1 \) and \( c_2 \) known the contact microhardness can be determined by using equation 5.8. The results are summarised below. The unit of the roughness, \( \sigma \), is in \( \mu \text{m} \). and for the microhardness is GPa.

For SS 304

\[
H_c = 9.507 \left( \frac{0.95\sigma}{m} \right)^{-0.3738}
\]

For NILO 36

\[
H_c = 3.857 \left( \frac{0.95\sigma}{m} \right)^{-0.1635}
\]

For Al 6060

\[
H_c = 0.938 \left( \frac{0.95\sigma}{m} \right)^{-0.0791}
\]

Figure 5.8 is the picture of the specimens. To the left is the SS 304 specimen, Al 6060 at the centre and NILO 36 to the right. Figure 5.9a, 5.9b and 5.9c are the enlarged pictures of the blasted surfaces of specimen nos. S1A, N10A, and A23. Refer to Table 5.2 for the type of abrasive used, blasting pressure and the surface characteristics.
Figure 5.8 Test Specimens. To the left is the SS 304 specimen, Al 6060 at the centre then NILO 36 to the right.
Figure 5.9 Enlarged Pictures of Blasted Surfaces. (a) SS 304 blasted with garnet, 30/60 mesh at 550 kPa blasting pressure. (b) NILO 36 blasted with aluminium oxide, size 80 at 550 kPa. (c) Aluminium 6060 blasted with glass beads, 90-45 μm at 100 kPa.
CHAPTER 6
VALIDATION OF THE THEORETICAL MODEL ON THERMAL
RECTIFICATION

This chapter presents the validation of the theoretical model on thermal rectification of similar and dissimilar metals under vacuum and varying contact pressure discussed in chapter 3. Eighteen pairs of specimens were used for the eighteen experiments conducted for this particular area of the research. Fifteen were for similar specimens and three for dissimilar specimens. For the similar specimens, five pairs of SS 304 materials, four pairs of NILO 36 and six pairs of Al 6060 were used. For the dissimilar specimens, three pairs of SS 304 and Al 6060 materials were used for the experiments. The experimental results were then compared with the numerical calculations using the theoretical model.

The experiments were conducted with the following conditions and requirements being observed:

1. The tests should be conducted in vacuum.
2. The two heat flux meters and two specimens should be properly aligned.
3. The acquisition of temperature readings was done only when the temperature had stabilised.
4. The correlation coefficient between the actual thermocouple readings and temperature obtained by using the linearised equation should not be less than 99%.
5. The heat flux readings of the top and bottom heat flux meters should not differ by more than 5% of the average of the two.
6. Reversal of the heat flow was done only when the maximum temperature reading had gone down to not more than 30°C above the room temperature.

Each experiment would take around one week in the average to finish.
6.1 Experiments on Specimens of Similar Materials

The following are the results of the experiments using specimens of the same materials using Stainless Steel SS 304:

Specimens: Spherical end and Flat end / SS 304 material

The theoretical model as described in chapter 3 focuses on the theory that thermal rectification of similar metals occurs due to the difference in the heat transfer contact area as the flow of heat is reversed. The contact area depends on the geometrical configuration of the contacting surfaces. The theoretical model assumes two spherically shaped asperities to be in contact with each other. Thermal rectification based on the model will occur if the heat flows from the asperity with smaller radius to the asperity with a larger radius. To verify this theory on a larger scale, two specimens were specially fabricated. The material for the specimens is SS 304 and they were fabricated from the same bar stock. The shape of one specimen is similar to the ones used in the other experiments. The other however has one end spherically shaped. Both ends of the two specimens were mirror finished. Figure 6.1 shows the schematic drawing of the specimen with one end spherically shaped. Figure 6.2 is the photograph of the specially fabricated specimens.

The determination of the thermal contact conductance in this experiment was done using a procedure different from the other experiments. Figure 6.3 illustrates the temperature variation along the lengths of the two heat flux meters and the two contacting specimens. The temperature drop through the contact of the heat flux meter and the specimen is minimal because a heat transfer paste for reducing the thermal contact resistance was applied in between the contacting surfaces. The diagram is only for a particular contact pressure and for the case where the heat flow is from left to right. The temperature readings of the thermocouples attached to the two specimens are not used in the calculation because they are considered to be within the
disturbed region. Only the readings of the thermocouples attached to the two heat flux meters are utilised for the determination of the thermal contact conductance.

Figure 6.1 Schematic Diagram of the Specimen with One End Spherically Shaped
Figure 6.2 Picture of the Two Specially Fabricated Specimens. To the left is the specimen with both ends flat and to the right is the specimen with one end flat and the other end spherical.
Figure 6.3 Temperature Variation along the Lengths of the Two Heat Flux Meters and the Two Test Specimens
From the above figure the temperatures $T_1$ and $T_2$ can be computed by using the linear equations that are obtained by linearising the thermocouple readings $T_a$, $T_b$, $T_c$ and $T_d$, $T_e$, $T_f$ respectively. The thermal contact conductance is then calculated by using the following formulas:

$$h_c = \frac{q}{T_1 - T_2 - \Delta T_{\text{SOLID}}} \quad 6.1$$

The temperature drop $\Delta T_{\text{SOLID}}$ is the drop in temperature for a solid specimen that is equivalent to two specimens connected from end to end. The length of the solid specimen is equal to the total of the lengths of the two specimens. Since the thermal conductivity of the similar material specimens is known the $\Delta T_{\text{SOLID}}$ can be calculated using the well-known Fourier equation for heat conduction as presented below:

$$q = -k \frac{dT}{dX} \quad 6.2$$

If we let $k = \alpha + \beta T$, total length = L and then plugging them into equation 6.2 the equation after integrating from $T_1$ to $T_{2s}$ is

$$q = -\frac{1}{L} \left[ \left( \alpha T_2 + \frac{\beta T_{2s}^2}{2} \right) - \left( \alpha T_1 + \frac{\beta T_1^2}{2} \right) \right] \quad 6.3$$

With $q$, $\alpha$, $\beta$, $L$ and $T_1$ known, $T_{2s}$ can be computed using equation 6.3. Then $\Delta T_{\text{SOLID}}$ is calculated as the difference between $T_1$ and $T_{2s}$. For stainless steel SS 304 the values of $\alpha$ and $\beta$ as given in chapter 5 are 14.602 and 0.01232 respectively. The value of $L$ is 0.050 m. and is equal to the sum of the lengths of the two specimens. Using equation 6.1 the thermal contact conductance can then be obtained. The same procedure is used if the heat flow direction is reversed.
Figure 6.4 shows the plots of the thermal contact conductance versus contact pressure for both directions of heat flow. The figure indicates a clear trend of positive thermal rectification if the flow is from the specimen with spherical end to a specimen of flat end. The results validate the theory that thermal rectification for similar materials does occur due mainly to the geometrical shape of the contacting surfaces and that the thermal contact conductance is higher if the flow is from a smaller radius sphere to a larger sphere. In this case it is a contact of two spherically shaped surfaces with one having a radius of curvature of 21.25 mm. (spherical end) and the other with a radius approaching infinity (flat end).

Figure 6.4 Plots of the Results of the Experiments for Both Directions of Heat Flow for Specimens SS 304 with Spherical End and SS 304 with Flat End
Nominally flat and Smooth Specimens: S5 and S6 / SS 304 material

Figure 6.5 shows the conductance versus the contact pressure plots of the results of the experiment and the values based on the calculation using the theoretical model. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table. The average radius of asperity is calculated using equation 3.27 or equation 3.28.

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness(σ) in μm</th>
<th>Slope(m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S5/ SS 304</td>
<td>0.5853</td>
<td>0.0790</td>
<td>47.187</td>
</tr>
<tr>
<td>S6/ SS 304</td>
<td>0.8683</td>
<td>0.1067</td>
<td>38.553</td>
</tr>
</tbody>
</table>

It is clear that the experimental results indicate no significant rectification for this pair. The theoretical model also does not indicate a significant rectification. This is because the radii of the asperities do not differ much. Based on the theoretical model, for similar materials, thermal rectification will only occur if the contacting specimens have very different radii of asperities. And the results of the experiment just described with positive thermal rectification (increase in thermal contact conductance) occurring if the heat flows from the surface of smaller radius of asperity to a surface of larger radius of asperity.
Figure 6.5 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens S5 and S6
Nominally flat Rough Specimens: S6X and S21 / SS 304 material

Figure 6.6 shows the conductance versus the contact pressure plots of the results of the experiment and the values based on the calculation using the theoretical model. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table:

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness(σ) in μm</th>
<th>Slope(m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6X/ SS 304</td>
<td>1.8040</td>
<td>0.4607</td>
<td>5.152</td>
</tr>
<tr>
<td>S21/ SS 304</td>
<td>5.5080</td>
<td>0.6021</td>
<td>10.351</td>
</tr>
</tbody>
</table>

The experimental results indicate positive thermal rectification if the heat flows from S6X to S21. The results agree well with the theoretical calculation. It is shown that there is an increase in thermal contact conductance if the heat flows from a smaller radius of asperity to a larger radius asperity. It must be noted that in this case S6X is smoother than S21.
Figure 6.6 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens S6X and S21
Nominally flat, Smooth and Rough Specimens: S14X and S20 / SS 304 material

Figure 6.7 gives the conductance versus the contact pressure plots of the results of the experiment and the values based on the calculation using the theoretical model. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table:

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness((\sigma)) in (\mu)m</th>
<th>Slope((m)) in radians</th>
<th>Asperity radius in (\mu)m</th>
</tr>
</thead>
<tbody>
<tr>
<td>S14X/ SS</td>
<td>0.5562</td>
<td>0.3741</td>
<td>2.265</td>
</tr>
<tr>
<td>S20/ SS 304</td>
<td>4.6230</td>
<td>0.5854</td>
<td>9.057</td>
</tr>
</tbody>
</table>

The experimental results indicate positive thermal rectification if the heat flows from S14X to S20. The results agree well with the theoretical calculation. The experimental results validate the theory that there is an increase in thermal contact conductance if the heat flows from a smaller radius of asperity to a larger radius asperity. Take note that S14X is smoother than S20.
Figure 6.7 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens S14X and S20
Nominally flat Rough and Smooth Specimens: S7 and S8 / SS 304 material

Figure 6.8 gives the conductance versus the contact pressure plots of the results of the experiment. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table:

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness(σ) in μm</th>
<th>Slope(m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7/ SS 304</td>
<td>2.4587</td>
<td>0.3697</td>
<td>10.225</td>
</tr>
<tr>
<td>S8/ SS 304</td>
<td>0.5950</td>
<td>0.0847</td>
<td>41.800</td>
</tr>
</tbody>
</table>

The experimental results clearly indicate positive thermal rectification if the heat flows from S7 to S8. The experimental results validate the theory that there is an increase in thermal contact conductance if the heat flows from a smaller radius of asperity to a larger radius asperity. In this case S7 is rougher than S8, which is different from the two pairs previously discussed. It indicates that the direction of heat flow for positive thermal rectification of similar materials can not be predicted by knowing the roughness or smoothness alone.
Figure 6.8 Plots of the Results of the Experiments Using Specimens S7 and S8
The following are the experiments on specimens of the same material using NILO 36:

Nominally flat Rough and Smooth Specimens: N7 and N8 / NILO 36 material

Figure 6.9 gives the conductance versus the contact pressure plots of the results of the experiment and the values based on the calculation using the theoretical model. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table:

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness(σ) in μm</th>
<th>Slope(m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7/ NILO 36</td>
<td>2.4800</td>
<td>0.3697</td>
<td>10.330</td>
</tr>
<tr>
<td>N8/ NILO 36</td>
<td>0.7627</td>
<td>0.0847</td>
<td>31.520</td>
</tr>
</tbody>
</table>

The experimental results clearly indicate positive thermal rectification if the heat flows from N7 to N8. The results agree well with the theoretical calculation. The experimental results validate the theory that there is an increase in thermal contact conductance if the heat flows from a smaller radius of asperity to a larger radius asperity.
Figure 6.9 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens N7 and N8
Nominally flat Smooth and Rough Specimens: N9 and N10 / NILO 36 material

Figure 6.10 gives the conductance versus the contact pressure plots of the results of the experiment and the values based on the calculation using the theoretical model. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table:

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness(σ) in μm</th>
<th>Slope(m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N9/ NILO 36</td>
<td>0.6627</td>
<td>0.1013</td>
<td>32.600</td>
</tr>
<tr>
<td>N10/ NILO 36</td>
<td>2.4887</td>
<td>0.3850</td>
<td>9.640</td>
</tr>
</tbody>
</table>

The experimental results clearly indicate positive thermal rectification if the heat flows from N10 to N9. The results agree well with the theoretical calculation. The experimental results validate the theory that there is an increase in thermal contact conductance if the heat flows from a smaller radius of asperity to a larger radius asperity.
Figure 6.10 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens N9 and N10
Nominally flat Rough and Smooth Specimens: N11 and N12 / NILO 36 material

Figure 6.11 gives the conductance versus the contact pressure plots of the results of the experiment and the values based on the calculation using the theoretical model. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table:

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness(σ) in μm</th>
<th>Slope(m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N11/ NILO 36</td>
<td>2.8987</td>
<td>0.3730</td>
<td>11.866</td>
</tr>
<tr>
<td>N12/ NILO 36</td>
<td>0.6415</td>
<td>0.1025</td>
<td>30.850</td>
</tr>
</tbody>
</table>

The experimental results clearly indicate positive thermal rectification if the heat flows from N11 to N12. The results agree well with the theoretical calculation. The experimental results validate the theory that there is an increase in thermal contact conductance if the heat flows from a smaller radius of asperity to a larger radius asperity.
Specimens: N11 and N12

Figure 6.11 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens N11 and N12
Figure 6.12 gives the conductance versus the contact pressure plots of the results of the experiment and the values based on the calculation using the theoretical model. The rms roughness, slope and average radius of the asperities of these specimens are given in the following table:

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness(σ) in μm</th>
<th>Slope(m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N12X/ NILO</td>
<td>3.4944</td>
<td>0.5925</td>
<td>6.724</td>
</tr>
<tr>
<td>N4/ NILO 36</td>
<td>5.6320</td>
<td>0.6243</td>
<td>10.040</td>
</tr>
</tbody>
</table>

The experimental results indicate positive thermal rectification if the heat flows from N12X to N4. The results agree well with the theoretical calculation. The experimental results validate the theory that there is an increase in thermal contact conductance if the heat flows from a smaller radius of asperity to a larger radius asperity.
Figure 6.12 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens N12X and N4
6.2 Experiments of Specimens of Similar Material Using Aluminium Al 6060

In tests dealing with aluminium specimens, it should be noted that oxide layer will cover the test surfaces and a correction for the oxide layer effect was made as described below:

Prior to testing the specimens had been stored in individual cubicles made of cardboard. An array of cubicles inside a metallic box shown in figure 6.13 was used for the storage of all specimens. The specimens were grouped in accordance with the material type and they were covered with clean cotton cloth. The experiments on thermal rectification of similar materials under a vacuum environment using aluminium Al 6060 specimens were performed after stainless steel SS 304 and NILO 36. It took more than 6 months of storage before the experiments for aluminium were started. The main purpose of the longer storage before doing the experiment was to make certain that the formation of aluminium oxide had already attained the stage of very low growth rate. Since the formation of aluminium oxide is inevitable then the experiments were done with the knowledge that aluminium oxide had already formed. The longer storage ensured that the formation of the aluminium oxide had almost stabilised and can be considered constant within the duration of the experiment.

Aluminium oxide is immediately formed when aluminium material is exposed to an environment with oxygen. A thickness of 10 Angstrom (0.001μm) is formed within seconds of freshly exposed metal. In this process the substrate is the one converted to oxide layer so the surface characteristics of the specimen are not affected. The oxidation of aluminium at room temperature is reported to conform to an inverse logarithmic equation for growth periods of up to 5 years (Godard, 1967). At elevated temperatures, oxidation studies over a shorter period of time illustrate conformity to parabolic, linear and logarithmic relationships (Gulbransen and Wysong, 1947). The oxide formed possesses some protective properties but does not
entirely resist damp conditions. Hart (1956) showed that in dry oxygen the film ceases to grow when a certain value is reached after a rapid thickening, however in damp oxygen it does not come to an end but continuous at a slow rate.

Figure 6.13 Box for the Storage of Test Specimens

The formation of aluminium oxide can be artificially done by anodising. Peterson and Fletcher (1990) investigated the thermal contact conductance and thermal conductivity of anodised aluminium coatings. They found out that the overall joint conductance decreased with increasing thickness of the anodised coating and increased with increasing interfacial load. They found out also that the thermal conductivity of the anodised coating is approximately
Lambert et al. (1993) did a similar work on hard and soft coat anodised aluminium.

The theoretical model for the numerical calculation of thermal contact conductance has incorporated the effect of aluminium oxide layer. The layer of each specimen is considered to be an additional resistance to the flow of heat. So the total resistance is considered to be equal to the sum of contact resistance and the resistance due to the oxide layer of each specimen. It is presented in equation form below:

\[ R_{\text{total}} = R_c + R_1 + R_2 \]

where:
- \( R_c \) = thermal contact resistance,
- \( R_1 \) = resistance due to the oxide layer on specimen 1
- \( R_2 \) = resistance due to the oxide layer on specimen 2

By expressing the resistance in terms of heat flux, temperature drop, and thickness and thermal conductivity of the oxide layer, equation 6.4 becomes:

\[ \frac{\Delta T_{\text{total}}}{q} = \frac{\Delta T_c}{q} + \frac{x_1}{k_{x1}} + \frac{x_2}{k_{x2}} = \frac{1}{h_{\text{total}}} \]

Therefore,

\[ h_{\text{total}} = \frac{q}{\Delta T_c + \left( q \frac{x_1}{k_x} \right) + \left( q \frac{x_2}{k_x} \right)} \]

where:
- \( h_{\text{total}} \) = total thermal contact conductance, W/m\(^2\)-K
- \( q \) = heat flux, W/m\(^2\)
- \( \Delta T_c \) = contact temperature drop, K
- \( x_1, x_2 \) = oxide layer thickness on specimens 1 and 2 respectively, m
- \( k_x \) = thermal conductivity of oxide layer, W/mK
The theoretical model can calculate the contact temperature drop. However the value of the resistance of the oxide layer expressed as \( x/k \) is not readily available. Although the thermal conductivity was determined by Peterson and Fletcher (1990), the thickness of the oxide layer is not known making the calculation of \( x/k \) difficult. The aluminium specimens were placed in an environment where the mechanism of the oxide formation is very complex. Although visual inspection of the surface indicated formation of the film, its thickness could not be determined without damaging the surface characteristics. A semi-empirical relationship is proposed in order to solve the problem of determining the oxide layer resistance. The semi-empirical expression is obtained based on the following qualitative analysis:

Figure 6.14 illustrates the schematic diagram of the surfaces of the contacting aluminium specimens.

---

**Legend:**
- oxide layer
- substrate

**Figure 6.14 Contact of Two Aluminium Specimens with Oxide Layers**
The figure above shows that at low contact pressure the contact is all oxide layer to oxide layer contact. As the contact pressure increases the oxide layer at some spots fractures resulting to substrate to substrate contact in some areas. The net result is a decrease in the oxide layer resistance. This trend continues as the contact pressure increases. However if the principle of conservation of volume is to be applied it is expected that the resistance will continue to decrease and approach asymptotically to a limiting value as the contact pressure further increases until there is no more empty space in the junction. Figure 6.15 illustrates the behaviour of the oxide layer resistance with contact pressure. The curve in this figure follows the equation given below.

\[
\frac{x}{k_x} = C_1 e^{-c_2 P} + C_3 \quad 6.6
\]

where \( C_1 \) is the oxide layer resistance at no contact pressure and \( C_2 \) and \( C_3 \) are constants to be determined from experimental results.

The values of the constants used are 0.000025, 0.0002 and 0.0000 for \( C_1 \), \( C_2 \) and \( C_3 \) respectively. The value of \( C_1 \) is obtained by considering the thickness of the oxide layer as equal to 0.5\( \mu \)m at no contact pressure and using 0.02 W/mK as the thermal conductivity of the aluminium oxide layer. Plugging these values into equation 6.6 would result to the following equation for the oxide layer contact resistance:

\[
\frac{x}{k_x} = 0.000025 e^{-0.0002 P} \quad 6.7
\]
The above expression is incorporated in the equation for the total thermal contact conductance of pairs of aluminium specimens and pairs of aluminium and stainless steel SS 304 specimens (equation 6.5).

Figure 6.15 Proposed Plot of the Oxide Layer Contact Resistance vs. Contact Pressure

A summary of the experimental results and theoretical calculation is presented below:
Nominally flat Rough Specimens: A1 and A2/ Al 6060 material

Figure 6.16 shows the plots of the experimental results and numerical calculation using the theoretical model. The effective roughness of the contacting surface is 2.5814 μm. The radii of the asperities are 20.4 and 20.04 μm for specimens A1 and A2 respectively. The model predicts no thermal rectification. The experimental results indicate no clear trend of thermal rectification thus validating the prediction of the model.

Nominally flat Rough Specimens: A3 and A4/ Al 6060 material

The results are shown in figure 6.17. The effective roughness of the contacting surfaces is 2.4064 μm. The radii of the asperities are 20.446 and 20.0032 μm for specimens A3 and A4 respectively. No thermal rectification is shown by both the experimental and theoretical results.

Nominally flat Rough Specimens: A5 and A6/ Al 6060 material

Figure 6.18 presents the plots of the experimental and theoretical results. The effective roughness of the contacting surfaces is 2.4088 μm. The radii of the asperities are 20.977 and 19.864 μm for specimens A5 and A6 respectively. Both results indicate no thermal rectification.

Nominally flat Rough Specimens: A7 and A8/ Al 6060 material

Figure 6.19 gives the results of both the experimental and theoretical calculation. The effective roughness of the contacting surfaces is 2.5954 μm. The radii of the theoretical asperity are 20.580 and 19.725 μm for specimens A7 and A8 respectively. No thermal rectification is indicated by both.

Nominally flat Rough Specimens: A26 and A13X/Al 6060 material

Figure 6.20 shows the plots of the theoretical and experimental results. The effective roughness of the contacting surfaces is 7.969 μm. The radii of
the asperities are 6.6500 and 12.494 \( \mu \text{m} \) for specimens A26 and A13X respectively. The effective roughness of this pair is higher compared with the previously discussed pairs and its results should indicate a lower thermal contact conductance. However, both theoretical and experimental results are slightly higher than those discussed previously. The reason is that the asperities of this pair are peakier as indicated by their lower values. The peakier the asperity is the lesser is the resistance to deformation, thus a greater heat transfer area and higher thermal contact conductance. The theoretical values agree well with the experimental. With regards to thermal rectification both results do not indicate a clear trend of thermal rectification.

**Nominally flat Rough and Smooth Specimens: A25 and A21X/ Al 6060 material**

The plots of both theoretical and experimental results are given by figure 6.21. The effective roughness of the contacting surfaces is 2.77\( \mu \text{m} \). The radii of the asperities are 6.692 and 2.902 \( \mu \text{m} \) for specimens A25 and A21X respectively. The effective roughness is almost the same as the previously discussed pairs except for the recently presented pair, A26 and A13. However the thermal contact conductance is higher. The reason is the same as with the pair recently discussed, i. e., it is peakier. With regards to the directional effect, there is a clear trend of thermal rectification shown by both results. Although the thermal rectification indicated by the theoretical model is lower than the experimental results, they both agree that thermal rectification occurs from specimen A21X to A25.
Figure 6.16 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens A1 and A2
Specimens: A3 and A4

![Graph showing conductance vs. contact pressure for Specimens A3 and A4.]

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness ($\sigma$) in $\mu$m</th>
<th>Slope (m) in radians</th>
<th>Asperity radius in $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3/ Al 6060</td>
<td>1.9927</td>
<td>0.2263</td>
<td>20.446</td>
</tr>
<tr>
<td>A4/ Al 6060</td>
<td>1.3490</td>
<td>0.1867</td>
<td>20.003</td>
</tr>
</tbody>
</table>

Figure 6.17 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens A3 and A4
Specimens: A5 and A6

![Graph showing conductance vs contact pressure for Specimens A5 and A6.]

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness (σ) in μm</th>
<th>Slope (m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A5/ Al 6060</td>
<td>1.5167</td>
<td>0.1937</td>
<td>20.977</td>
</tr>
<tr>
<td>A6/ Al 6060</td>
<td>1.8713</td>
<td>0.2223</td>
<td>19.864</td>
</tr>
</tbody>
</table>

Figure 6.18 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens A5 and A6
Specimens: A7 and A8

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness ($\sigma$) in $\mu$m</th>
<th>Slope (m) in radians</th>
<th>Asperity radius in $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7/ Al 6060</td>
<td>2.2297</td>
<td>0.2393</td>
<td>20.580</td>
</tr>
<tr>
<td>A8/ Al 6060</td>
<td>1.3283</td>
<td>0.1867</td>
<td>19.725</td>
</tr>
</tbody>
</table>

Figure 6.19 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens A7 and A8
Specimens: A26 and A13X

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness (σ) in μm</th>
<th>Slope (m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A26/AI 6060</td>
<td>2.5640</td>
<td>0.4887</td>
<td>6.650</td>
</tr>
<tr>
<td>A13X/AI 6060</td>
<td>7.5452</td>
<td>0.6577</td>
<td>12.494</td>
</tr>
</tbody>
</table>

Figure 6.20 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens A26 and A13X
Specimens: A25 and A21X

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness (σ) in μm</th>
<th>Slope (m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A25/Al 6060</td>
<td>2.6561</td>
<td>0.4976</td>
<td>6.692</td>
</tr>
<tr>
<td>A21X/Al 6060</td>
<td>0.7864</td>
<td>0.3959</td>
<td>2.902</td>
</tr>
</tbody>
</table>

Figure 6.21 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens A25 and A21X
6.3 Experiments On Specimens of Dissimilar Materials

The materials used in each pair of specimens are stainless steel SS 304 and aluminium Al 6060. The effect of the formation of oxide layer is considered in the theoretical model. The summary of results is given below:

Nominally flat Rough Specimens: A13 and S11

Figure 6.22 shows the plots of the experimental and theoretical results. The effective roughness of the contacting surfaces is 4.1894 μm. The radii of the asperities are 6.740 and 5.916 μm for specimens S11 and A13 respectively. The theoretical model predicts a slight thermal rectification from specimen A13 to S11 however the experimental results do not indicate a clear trend of which direction of heat flow rectification occurs.

Nominally flat Rough Specimens: A21 and S13

The results of the experiment and the theoretical model are plotted in figure 6.23. The effective roughness of the contacting surfaces is 4.3190μm. The radii of the theoretical asperities are 7.328 and 6.493 μm for specimens A21 and S13 respectively. The plots agree very well. The theoretical model predicts that thermal rectification occurs if the heat flow is from A21 to S13. The experimental results also indicate that thermal rectification occurs from A21 to S13.

Specimens: A12 and S14

Figure 6.24 give the plots of the experimental and theoretical results. The effective roughness of the contacting surfaces is 4.1331μm. The radii of the theoretical asperities are 6.480 and 5.320μm for specimens S14 and A12 respectively. There is a good agreement between the two except at high contact pressure where the experimental results give a very large percentage of thermal rectification.
Specimens: S11 and A13

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness (σ) in μm</th>
<th>Slope (m) in radians</th>
<th>Asperity radius in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11/SS 304</td>
<td>3.551</td>
<td>0.5980</td>
<td>6.740</td>
</tr>
<tr>
<td>A13/Al 6060</td>
<td>2.223</td>
<td>0.4810</td>
<td>5.916</td>
</tr>
</tbody>
</table>

Figure 6.22 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens S11 and A13
Figure 6.23 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens S13 and A21
Specimens: S14 and A12

<table>
<thead>
<tr>
<th>Specimen No./material</th>
<th>Roughness ($\sigma$) in $\mu$m</th>
<th>Slope (m) in radians</th>
<th>Asperity radius in $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>S14/SS 304</td>
<td>3.6323</td>
<td>0.6240</td>
<td>6.480</td>
</tr>
<tr>
<td>A12/Al 6060</td>
<td>1.9720</td>
<td>0.4770</td>
<td>5.320</td>
</tr>
</tbody>
</table>

Figure 6.24 Plots of the Results of the Experiments and Numerical Calculation Using the Theoretical Model for Both Directions of Heat Flow for Specimens S14 and A12
6.4 General Observations of the Theoretical and Experimental Results on Thermal Contact Conductance of Similar and Dissimilar Metals Under Vacuum Environment

The following are observed on the theoretical and experimental results on thermal contact conductance of similar and dissimilar metals under vacuum:

1) For similar metals the thermal rectification occurs from the specimen with smaller radius to the specimen with the larger radius of asperity. All of the experimental results validate the theoretical prediction of the occurrence of thermal rectification.

2) For similar effective roughness the pair with smaller radii of asperities has higher thermal contact conductance, i.e. the peakier the asperities of the contacting surfaces the higher the conductance for a similar effective roughness.

3) The aluminium oxide layer reduces the thermal contact conductance. Its influence is quite considerable at high contact pressure as shown in figure 6.24. The results plotted in the figure is based on the theoretical model using At low contact pressure the resistance due to the oxide layer is relatively small compared with the total contact resistance. As the contact pressure increases the contacting asperities deforms resulting to an increase in the contact heat transfer area and subsequently decrease in total contact resistance. The contact resistance due to oxide layer also decreases and approaches asymptotically to a limiting value as the contact pressure increases. The limiting value is when the junction has no more empty space due to the deformation of the asperities as the contact pressure is applied. In the limiting value situation the oxide layer is still within the junction and providing resistance to the heat flow.
Figure 6.25 Influence of the Oxide Layer on the Total Contact Temperature Drop Based on the Theoretical Model
CHAPTER 7
EXPERIMENTS ON THE EFFECT OF INTERSTITIAL MATERIAL ON THERMAL CONTACT CONDUCTANCE

Thermal contact conductance can be enhanced or reduced by inserting a material in between the contacting surfaces to fill the voids in between the contact surfaces. Theoretically, the thermal contact resistance approaches zero if all voids are filled-up and the filler material has a thermal conductivity equal to or greater than the contacting material and that there is no contact resistance between the solid surfaces and the filler material. Figure 7.1 shows a schematic diagram when a metallic interstitial material is sandwiched between two contacting surfaces.

Figure 7.1 Heat Flow through an Interface with a Foil Insert under Vacuum
The filling-up of the voids by the metallic foil depends largely on the contact pressure, roughness and hardness of the contacting surfaces, and foil hardness and thickness. For a pair of contacting surfaces and particular type of foil, there is an optimum thickness at which the thermal contact conductance is maximum, (Babus’haq et al., 1991; O’Callaghan et al., 1983; Yovanovich, 1972). Thicker foils would tend to separate the contacting surfaces to a considerable distance resulting in additional resistance. The thick foil may not also easily conform to the contour of the contacting surfaces. On the other hand, use of foils thinner than the optimum would result in unfilled voids.

The experiments on the effect of metallic foils were conducted with the following conditions and requirements being observed:

1. Test should be conducted in vacuum.
2. The two heat flux meters and two specimens with the metallic foil in between should be properly aligned.
3. The metallic foil should be circular in shape and have a diameter equal to the diameter of the specimens. It should be cleaned with ethanol before inserting into the contact area.
4. The correlation between the actual thermocouple readings and temperature obtained by using the linearised equation should not be less than 99 %.
5. The heat flux meter readings of the top and bottom heat flux meters should not differ by more than 5 % of the average of the two.

The experiments used different thicknesses of metallic inserts for a particular roughness of the contacting surfaces. The materials for the inserts were aluminium foils and gold leaves. The materials for the test specimens were NILO 36 and stainless steel SS 304. For each pair of specimens the thickest insert was used first followed by foils of next lesser thickness and eventually the bare contact. This procedure ensures that the surface is not considerably damaged with the application of contact pressure. This
procedure is used because the metallic inserts have a much lesser hardness than the test specimens.

The thickness of the aluminium foils was determined using a digital micrometer. Three sizes of aluminium foils were used: 0.008 mm., 0.009 mm. and 0.017 mm. thick. The thickness of the gold leaf is 150 nanometre. It was measured in the School of Material Science of the University of New South Wales using an X-ray diffraction Spectrometer. The details of the metallic foils used in the experiments are given in the following table:

<table>
<thead>
<tr>
<th>Foil Material</th>
<th>Thickness, µm</th>
<th>Thermal conductivity, W/m-K</th>
<th>Hardness, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminium</td>
<td>8.00</td>
<td>204</td>
<td>265</td>
</tr>
<tr>
<td>aluminium</td>
<td>9.00</td>
<td>204</td>
<td>265</td>
</tr>
<tr>
<td>aluminium</td>
<td>17.00</td>
<td>204</td>
<td>265</td>
</tr>
<tr>
<td>gold</td>
<td>0.15</td>
<td>315</td>
<td>294</td>
</tr>
</tbody>
</table>

7.1 Experimental Results and Discussion

The following are the results and discussion of the experiments using three pairs of stainless steel SS 304 and NILO 36 test specimens and aluminium foils and gold leaves. The range of the contact pressure in the experiment is from 196 kPa to 4500 kPa; for the mean junction temperature, from 65°C to 85°C and the vacuum attained is 0.0014 mbar.

Specimens: SS 304 (S3) and NILO 36 (N2)

Figure 7.2 shows the results of the experiments using stainless steel SS 304 (S3) and NILO 36 (N2) test specimens. The effective roughness of the contacting surfaces is 6.6200 µm. Three foils were used. An experiment with no foil was also conducted. The experimental results indicate that with an aluminium foil of 8µm thick the thermal contact conductance has increased by more than 500 % compared with that of the bare junction. The conductance with a 9µm thick aluminium foil is slightly higher compared with the 8µm thick
aluminium foil. However with a 17μm thick aluminium foil the conductance does not increase compared with the 9μm thick foil but instead it decreases slightly. This indicates that the optimum thickness is somewhere in between 9μm and 17μm and that the value is nearer to 17μm than 9μm.

A numerical calculation of the no foil case was performed using the theoretical model discussed in chapter 3. It can be observed from figure 7.2 that the theory underpredicts the conductance for the bare joint. The theory is based on the fresh configuration of the surfaces whereas the experiment with bare joint is based on surfaces that are previously loaded, i.e., the whole range of contact pressure with 17μm aluminium foil; with 9μm aluminium foil; and then with 8μm aluminium foil. The previous loading slightly deformed the contacting asperities thus resulting to a higher conductance compared with the fresh contacting surfaces.

Table 7.1 summarises the thermal contact conductance as function of the foil thickness and contact pressure. The table indicates the following:

a) Conductance increases with increase in contact pressure whether there is foil or not;

b) Conductance increases with contact pressure, is larger for the joint with 8μm aluminium foil compared to the bare joint. Also the rate of conductance increase is greater for the joint with foil.

c) Conductance increases with contact pressure, is larger for the joint with 9μm aluminium foil compared to with 8μm aluminium foil except at low contact pressures of 196.49 and 314.38 kPa;

d) Conductance values are lower for the joint with 17μm of aluminium foil compared to with 9μm aluminium foil.
Specimens: SS 304 (S3) and NILO 36 (N2)

<table>
<thead>
<tr>
<th>Specimen/Material</th>
<th>rms Roughness, μm</th>
<th>rms Slope, Radians</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3/ SS 304</td>
<td>5.7067</td>
<td>0.3970</td>
</tr>
<tr>
<td>N2/ NILO 36</td>
<td>3.3553</td>
<td>0.4080</td>
</tr>
</tbody>
</table>

Figure 7.2 Contact Pressure – Thermal Contact Conductance Chart of Stainless Steel SS 304 (S3) and NILO 36 (N2) Test Specimens. Effective Roughness is 6.6200 μm.
<table>
<thead>
<tr>
<th>Contact Pressure (kPa)</th>
<th>Bare Joint Conductance</th>
<th>0.008 mm Conductance</th>
<th>0.009 mm Conductance</th>
<th>0.017 mm Conductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>196.49</td>
<td>332.94</td>
<td>1801.41</td>
<td>1641.89</td>
<td></td>
</tr>
<tr>
<td>314.38</td>
<td>485.17</td>
<td>2507.58</td>
<td>2482.93</td>
<td>1312.42</td>
</tr>
<tr>
<td>785.96</td>
<td>745.98</td>
<td>3719.89</td>
<td>3808.99</td>
<td>2628.67</td>
</tr>
<tr>
<td>1375.44</td>
<td>1070.06</td>
<td>3084.22</td>
<td>6306.32</td>
<td>4329.33</td>
</tr>
<tr>
<td>1964.91</td>
<td>1097.84</td>
<td>4116.15</td>
<td>7200.00</td>
<td>6603.14</td>
</tr>
<tr>
<td>2554.39</td>
<td>1603.17</td>
<td>5955.68</td>
<td>8769.30</td>
<td>8086.23</td>
</tr>
<tr>
<td>3143.86</td>
<td>1692.00</td>
<td>7000.37</td>
<td>14893.19</td>
<td>13353.75</td>
</tr>
<tr>
<td>3733.34</td>
<td>2242.39</td>
<td>14551.24</td>
<td>14393.69</td>
<td></td>
</tr>
<tr>
<td>4440.71</td>
<td>2403.59</td>
<td>15059.96</td>
<td>17915.74</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1 Thermal Contact Conductance as Function of the Aluminium Foil Thickness and Contact Pressure (SS 304 (S3)/NILO 36 (N2) Joint). This is based on figure 7.2.
Figure 7.3 shows the contact pressure – thermal contact conductance chart using S1 and N1 test specimens and different types of metallic inserts. The effective roughness of the contacting surfaces is 4.4514\(\mu\)m. The contact conductance with a 9\(\mu\)m aluminium foil is higher at contact pressure from 2500 kPa to 4400 kPa compared with 8\(\mu\)m aluminium foil. At contact pressure lower than 2500 kPa they have almost the same thermal contact conductance. This trend is similar to the experiment previously discussed where the conductance using 9\(\mu\)m aluminium foil is higher than with 8\(\mu\)m foil at high contact pressure and almost equal at low contact pressure. The conductance has reduced to around 50% throughout the whole contact pressure range when a 17\(\mu\)m aluminium foil is used. Instead of increasing as the thickness of the foil increases the conductance decreases. This indicates that the optimum thickness using aluminium foil is in between 9\(\mu\)m and 17\(\mu\)m and that the value is nearer to 9\(\mu\)m than 17\(\mu\)m. This is in contrast to the previous experiment where the optimum value was nearer to 17\(\mu\)m than 9\(\mu\)m. This can be explained by the fact that in the previous experiment, the effective roughness of the test specimens is higher (6.6200\(\mu\)m compared with 4.4514\(\mu\)m) and thus needed higher volume of material to fill the voids resulting in a greater optimum thickness.

The thermal contact conductance with four leaves of gold is lower than with the 9\(\mu\)m aluminium foil, 8\(\mu\)m aluminium foil and the 17\(\mu\)m aluminium foil at all contact pressures except at lower pressure. At lower pressure it is slightly higher than with the 17\(\mu\)m aluminium foil. Although gold has a higher thermal conductivity to hardness ratio compared with aluminium and thus has a better enhancement capability (Yovanovich, 1972) its total thickness is only 0.6000\(\mu\)m (four leaves at 0.1500\(\mu\)m per leaf). This means a smaller volume of the voids is filled-up resulting to a lesser increase in thermal contact conductance. The bare junction experiment was not possible to perform because the gold leaves that were used previously had stuck to the contacting
surfaces and could not be removed without damaging the surface. The thermal contact conductance without foil is approximated using the theoretical model discussed in chapter 3. The results suggest a lower value of conductance throughout the whole range of contact pressures. Table 7.2 shows the thermal contact conductance as function of the foil thickness and contact pressure.

| THERMAL CONTACT CONDUCTANCE |  
|-----------------------------|-----------------|------------------|-----------------|----------------|
| foil thickness              | contact pressure(kPa) | AI-0.008 mm | AI-0.009 mm | AI-0.017 mm | Gold-4 layers | Bare-Theory |
| 314.38                      | 975.11            | 1227.67       | 131.07       | 1646.62       | 273.67       |
| 668.07                      | 1380.33           |               |              |               |              |
| 785.96                      | 3103.22           | 3234.05       |              |               |              |
| 903.86                      | 1622.81           | 459.55        |              |               |              |
| 1139.65                     | 1866.39           |               |              | 2218.81       | 638.38       |
| 1375.44                     | 4750.19           | 4316.49       |              |               |              |
| 1611.23                     | 2387.23           |               |              | 2237.19       | 906.99       |
| 1964.91                     | 6000.00           | 6452.03       |              |               |              |
| 2318.60                     | 2898.39           |               |              | 2517.74       | 1172.88      |
| 2554.39                     | 8175.70           | 9246.76       |              |               |              |
| 3025.97                     | 3651.38           |               |              | 3046.68       | 1429.79      |
| 3143.86                     | 9785.50           | 12154.36      |              |               |              |
| 3733.34                     | 5144.72           | 3046.68       |              |               |              |
| 4440.71                     | 12065.82          | 12942.10      | 5423.16      | 3638.56       | 1690.45      |

Table 7.2 Thermal Contact Conductance as Function of the Foil Thickness and Contact Pressure (SS 304 (S1)/NILO 36 (N1) Joint). This is based on figure 7.3.
Specimens: SS 304 (S1) and NILO 36 (N1)

<table>
<thead>
<tr>
<th>Specimen/Material</th>
<th>rms Roughness, µm</th>
<th>Slope, Radians</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1/SS 304</td>
<td>0.3363</td>
<td>0.0800</td>
</tr>
<tr>
<td>N1/NILO 36</td>
<td>4.4387</td>
<td>0.4323</td>
</tr>
</tbody>
</table>

Figure 7.3 Contact Pressure – Thermal Contact Conductance Chart of Stainless Steel SS 304 (S1) and NILO 36 (N1) Test Specimens. Effective Roughness is 4.4514 µm.
Specimens: SS 304 (S2) and NILO 36 (N3)

Figure 7.4 presents the plots of the thermal contact conductance versus contact pressure of the experimental results using SS 304 and NILO 36 test specimens and different number of gold leaves as inserts. The effective roughness of the contacting surfaces is 0.927 μm. The results show an decrease in conductance throughout the whole range of the contact pressure as the number of gold leaves is decreased from five to no insert at all. The equivalent thickness of five leaves of gold is 0.750 μm. The results of the previous experiments indicate that the optimum thickness is greater than the effective roughness (around twice that of the effective roughness). Based on this the optimum thickness for this case should be greater than 0.750 μm. Table 7.3 presents the thermal contact conductance as function of the foil thickness and contact pressure.

<table>
<thead>
<tr>
<th>contact pressure(kPa)</th>
<th>bare</th>
<th>1 leaf-gold</th>
<th>3 leaves-gold</th>
<th>5 leaves-gold</th>
</tr>
</thead>
<tbody>
<tr>
<td>196.49</td>
<td>423.30</td>
<td>820.78</td>
<td>818.83</td>
<td>1623.16</td>
</tr>
<tr>
<td>314.38</td>
<td>569.61</td>
<td>1069.11</td>
<td>1256.43</td>
<td>2209.65</td>
</tr>
<tr>
<td>785.96</td>
<td>770.93</td>
<td>1439.99</td>
<td>2105.08</td>
<td>3830.10</td>
</tr>
<tr>
<td>1375.44</td>
<td>1082.10</td>
<td>1451.24</td>
<td>2436.60</td>
<td>4362.20</td>
</tr>
<tr>
<td>1964.91</td>
<td>1101.15</td>
<td>1868.88</td>
<td>3323.84</td>
<td>6111.02</td>
</tr>
<tr>
<td>2554.39</td>
<td>1277.55</td>
<td>2093.80</td>
<td>3207.30</td>
<td>6760.12</td>
</tr>
<tr>
<td>3143.86</td>
<td>1406.00</td>
<td>2397.18</td>
<td>3803.08</td>
<td>9912.62</td>
</tr>
<tr>
<td>3733.34</td>
<td>1778.18</td>
<td>2540.25</td>
<td>4442.75</td>
<td>11598.54</td>
</tr>
<tr>
<td>4440.71</td>
<td>1881.45</td>
<td>3057.13</td>
<td>5635.95</td>
<td>15255.69</td>
</tr>
</tbody>
</table>

Table 7.3 Thermal Contact Conductance as Function of the Foil Thickness and Contact Pressure (SS 304 (S2)/NILO 36 (N3) Joint). This is based on figure 7.4.
Specimens: SS 304 (S2) and NILO 36 (N3) with Gold Inserts

<table>
<thead>
<tr>
<th>Specimen/Material</th>
<th>rms Roughness, μm</th>
<th>rms Slope, Radians</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2/SS 304</td>
<td>0.5010</td>
<td>0.0717</td>
</tr>
<tr>
<td>N3/NILO 36</td>
<td>0.7800</td>
<td>0.1217</td>
</tr>
</tbody>
</table>

Figure 7.4 Contact Pressure – Thermal Contact Conductance Chart of Stainless Steel SS 304 (S2) and NILO 36 (N3) Test Specimens with Gold Leaf Inserts. Effective Roughness is 0.9270 μm.
7.2 General Discussion of the Experimental Results on the Effect of Metallic Inserts on Thermal Contact Conductance

The following are the overall observations on the results of the experiments on the effect of metallic inserts on the thermal contact conductance:

1) All of the results show that the thermal contact conductance increases with increase in contact pressure irrespective of whether the joint is bare or filled.

2) A metallic foil inserted in between two contacting surfaces can enhance the thermal contact conductance. Such an enhancement reaches a maximum for what maybe called the 'optimum thickness' of the insert.

Based on the results of the experiments and previous works of other investigators (Couedel et al. (1994), Marotta et al. (1994), Lambert and Fletcher (1993), Sauer (1992), Babus'haq et al. (1991), Kang et al. (1990), Fletcher (1988), Antonetti and Yovanovich (1988), Antonetti and Yovanovich (1985), O'Callaghan et al. (1983), Snaith et al. (1982), Fletcher (1972), Yovanovich (1972), Molgaard and Smeltzer (1970)) the subsequent qualitative analysis is proposed:

The insertion of the metallic foils in between the contacting surfaces can result in either of the following situations:

1) Contact between one specimen and one side of the metallic foil and contact of the other specimen and the other side of the foil.

2) Parts of the foil are torn due to the penetration of the asperities causing a substrate to substrate contact. The contact in this case is a combination of substrate to substrate contact and specimen to foil contact.
Contact Between One Specimen and One Side of the Metallic Foil and Contact of the Other Specimen and the Other Side of the Foil

This case can be treated as two contact resistances and one bulk resistance arranged in series. The theoretical model for the contact conductance discussed in chapter 3 can be used if the metallic foil is thick enough that warping or bending of the foil does not occur. This is illustrated in figure 7.5.

For the case where the thickness of the metallic foil is enough that warping or bending does not occur, the total resistance to the heat flow can be expressed as:

\[ R_{\text{total}} = R_1 + R_2 + R_{\text{bulk}} \tag{7.1} \]

Where:
\[ R_1, R_2 = \text{contact resistances of the two sides of the foil} \]
\[ R_{\text{bulk}} = \text{bulk resistance of the foil and computed as the thickness of the foil divided by its thermal conductivity} \]

The reciprocal of equation 7.1 is therefore the overall thermal contact conductance. This is given by equation 7.2 below.

\[ h_{\text{overall}} = \frac{1}{R_{\text{total}}} \tag{7.2} \]
Figure 7.5 Contact between One Specimen and one Side of the Metallic Foil and Contact of the Other Specimen and the Other Side of the Foil. (a) Foil is thick enough so that no warping has occurred. (b) Foil is not thick enough so that warping or bending has occurred.
For the determination of $R_1$, $R_2$, and $R_{\text{bulk}}$

Applying equations 7.1 and 7.2 into the pair S3 and N2 and with the 0.017 mm thick aluminium foil as the insert, the following results are obtained and discussed below:

$R_1$ is the resistance to heat flow at the contact of the stainless steel S3 specimen and one side of the aluminium foil. The roughness and slope of the S3 specimen as given in figure 7.2 are 5.7067 $\mu$m and 0.3970 radian. The roughness and slope of the aluminium foil are estimated to be 0.0500 $\mu$m and 0.0500 radians respectively. The surface of the foil is very smooth and the above approximation is based on the value for an almost mirror-finished surface. The foil is very smooth and not hard and the stylus of the profilometer tends to scratch the surface during surface roughness measurement resulting to a not very reliable reading. The effect in the numerical calculation of the roughness of the foil is almost negligible since its value is very small (for an almost mirror-finished surface) in comparison with the roughness of the S3 specimen. The resulting effective roughness of the contact used for the calculation is almost equal to the roughness of the S3 specimen. The following thermomechanical properties of the aluminium foil as obtained from Couedel et al. (1994) are used in the numerical calculation using the theoretical model discussed in chapter 3: thermal conductivity, 2.04 W/cm-K (204 W/m-K); hardness, 27.0 kg/mm$^2$ (265 MPa). The effect of the oxide layer formed on the surface of the aluminium foil is considered in the calculation. The thickness of the oxide layer is estimated to be equal to 20 Angstrom (0.002$\mu$m). This value is based on the discussion of oxide layer formation indicated in section 6.2 of chapter 6.

The calculation of $R_2$ is the same as the above except that the specimen considered is N3. The roughness and slope of N3 as given in figure 7.2 are 3.3553 $\mu$m and 0.4080 radians respectively.

The bulk resistance $R_{\text{bulk}}$ is computed as 17 $\mu$m divided by the thermal conductivity of 204 W/m-K resulting to $8.3333\times10^{-8}$ m$^2$-K/W, i.e. negligibly small.

The results of the calculation of $R_1$, $R_2$, the value of $R_{\text{bulk}}$, and the total resistance $R_{\text{total}}$ are plotted in figure 7.6. The corresponding overall thermal
contact conductance is plotted in figure 7.7 together with the experimental results that are obtained from figure 7.2. The agreement of the two plots in figure 7.10 is very good. At higher contact pressure the experimental values are higher and the model proposed may not hold as the deformation of the foil increases, i.e. we can no longer assume that there is no warping of the foil.

Figure 7.6 Theoretical Thermal Contact Resistance versus Contact Pressure Plot of the Contact of S3 and N2 Test Specimens with a 0.017 mm thick Aluminium Foil Insert.
Figure 7.7 Experimental and Theoretical Plots of the Total Thermal Contact Conductance versus Contact Pressure of S3 and N2 Test Specimens with a 0.017 mm thick Aluminium Foil Insert
CHAPTER 8
EXPERIMENTS ON THE DIRECTIONAL EFFECT ON GAS GAP
CONDUCTANCE

As stated earlier in chapter 1, the thermal joint conductance is the sum of
the solid spot conductance; the conductance due to the heat conduction
through the voids in between the contacting surfaces; and the conductance
due to the thermal radiation across the interface. With thermal radiation
considered negligible and with gas occupying the voids, the total thermal
conductance of a joint can be considered as the sum of the solid spot and gas
gap conductances. Figure 8.1 illustrates the heat flow through a contact of two
surfaces with a gas in between.

This chapter presents the results of the experiments on the directional
effect on thermal joint conductance with different gases at low contact
pressure. They are then compared with values calculated using the existing
equations and correlations on gas gap conductance. In the gas gap
conductance calculation a parameter that is not considered in the existing
methods of determining the gas gap conductance is introduced. This
parameter is the distortion of the nominally flat contacting surfaces as the heat
flows along the longitudinal axis of the test specimens. Three pairs of test
specimens; one pair of stainless steel SS 304 and NILO 36 specimens, and
two pairs of stainless steel SS 304 and aluminium Al 6060, were used in the
experiment. The pairs were tested in vacuum and in gas environments of
helium, argon, nitrogen and air.
Figure 8.1 Heat Flow through an Interface with Gas in Between
8.1 Theoretical Background

The convective mode of heat transfer for gap widths of up to around 6 mm is negligible (Lang, 1962) and, hence heat is transferred mainly by conduction in gaps of small widths. Thus, conduction is the principal mode of heat transfer in the experiments performed since the mean separation between contacting surfaces of the test specimens is three orders of magnitude less than 6 mm.

The thermal conductance of the joint as shown in figure 8.1 is the sum of the gas gap conductance and the solid spot conductance. The gas gap conductance can be calculated by applying the Fourier’s law of heat conduction as shown by equation 8.1 below.

\[ h_g = \frac{k_g}{\delta + g_1 + g_2} \]  

where:

- \( k_g \) = thermal conductivity of the gas, W/mK
- \( \delta \) = mean thickness of the gas gap, m
- \( g_1, g_2 \) = temperature jump distance for surfaces 1 and 2 respectively, m

The gases used in the experiments are argon, helium, nitrogen and air. Their properties can be found in published literature (Holman, 1986; Madhusudana, 1993; Perry, 1984). They are tabulated against temperature. From these tabulated values, the equation for the thermal conductivity of the gas as a function of temperature are obtained and presented in table 8.1.
<table>
<thead>
<tr>
<th>Gas</th>
<th>Thermal Conductivity, W/mK (T is in degrees Kelvin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>0.0049 + 0.00004 T</td>
</tr>
<tr>
<td>Helium</td>
<td>0.0535 + 0.0003 T</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.0071 + 0.00006 T</td>
</tr>
<tr>
<td>Air</td>
<td>0.0037 + 0.0000742 T</td>
</tr>
</tbody>
</table>

Table 8.1 Thermal Conductivities of Gases Used in the Experiments

The temperature jump distance is calculated using the equation by Kennard (1938) as given below:

\[ g = \left[ \frac{2 - \alpha}{\alpha} \right] \left[ \frac{2}{\gamma + 1} \right] \left[ \frac{k_g}{\mu C_v} \right] \lambda \tag{8.2} \]

where:
\[ \alpha = \text{thermal accommodation coefficient} \]
\[ \gamma = \text{ratio of specific heats} \]
\[ k_g = \text{thermal conductivity of the gas, W/mK} \]
\[ \mu = \text{viscosity, kg/m-s} \]
\[ C_v = \text{specific heat at constant volume, J/kg-K} \]
\[ \lambda = \text{mean free path of gas molecules, m} \]

The above parameters are readily obtainable from published literature (Holman, 1986; Madhusudana, 1993; Perry, 1984). Table 8.2 gives the viscosity of the gases as function of temperature.
Gas Viscosity (kg/m-s)

* T is in degree Kelvin

<table>
<thead>
<tr>
<th>Gas</th>
<th>Viscosity (kg/m-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>6E-06 + 6E-08 T</td>
</tr>
<tr>
<td>Helium</td>
<td>7E-06 + 4E-08 T</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>5E-06 + 4E-08 T</td>
</tr>
<tr>
<td>Air</td>
<td>4E-06 + 5E-08 T</td>
</tr>
</tbody>
</table>

Table 8.2 Viscosities of Gases as Function of Temperature

The values of the mean free path of gas molecule, $\lambda$, ratio of specific heats, $\gamma$, and the specific heat at constant volume, $C_v$, are obtained from Madhusudana (1996). They are based on ambient conditions and are shown in table 8.3.

<table>
<thead>
<tr>
<th>Gas</th>
<th>$\lambda$, (10^{-6}m)</th>
<th>$\gamma$</th>
<th>$C_v$, (J/kg-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>0.067</td>
<td>1.67</td>
<td>310</td>
</tr>
<tr>
<td>Helium</td>
<td>0.186</td>
<td>1.66</td>
<td>3150</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.063</td>
<td>1.40</td>
<td>741</td>
</tr>
<tr>
<td>Air</td>
<td>0.064</td>
<td>1.40</td>
<td>718</td>
</tr>
</tbody>
</table>

Table 8.3 Thermophysical Properties of the Gases Used in the Experiment

The thermal accommodation coefficient $\alpha$ is of great influence in controlling the temperature jump distance as shown by equation 8.2. It is a measure of the energy exchange between the gas molecules and the solid surfaces and is dependent on temperature and the nature of the gas and the solid surface. There exists a number of works dealing with experimental and theoretical determination of $\alpha$ (see, e.g., Hartnett, 1961; Wiedmann and Trumpler, 1946; Wachman, 1962; and Semyonov et al., 1984). Madhusudana
(1996) presents several equations and tabulated values obtained by a number of investigators. Thomas and Loyalka (1982) correlated their data for helium and obtained the following equation:

$$\alpha_{He} = 0.425 - 2.3(10^{-4})T$$

where $T$ is in degree Kelvin.

In the calculation of the temperature jump distance the following equation and values of the thermal accommodation coefficients are used:

1) Equation 8.3 is used in the calculation for the $\alpha$ of helium
2) For air the value is 0.9 as obtained from Madhusudana (1996)
3) For argon and nitrogen the accommodation coefficients are 0.90 and 0.78 respectively as estimated by Yovanovich (1993).

The mean thickness of the gas gap $\delta$ is of the same order of magnitude as the surface roughness heights. For contacting surfaces under a light mechanical load, Song et al. (1993) estimated the effective gap thickness as the maximum peak height of the rougher surface. The maximum peak height referred to be the height of the highest point of the profile above the mean line within the trace length. It is an extreme value characteristics of the surface roughness unlike other roughness parameters such as the rms height ($\sigma$) or the centre-line average height (CLA). For a good estimate of the maximum height, it should be measured based on sufficiently long trace length.

The distribution of surface heights about the mean height of a random rough surface is usually described by the Gaussian probability function with the standard deviation that is known as the surface roughness or rms height ($\sigma$). For a randomly rough surface, 99.3 % of the surface heights lie within the 3 standard deviations, i.e., $3\sigma$ of the mean value. The distance between the parallel mean planes of the surfaces in contact is the mean plane separation and can be equated to the mean thickness of the gas gap. It varies from a
value of $3\sigma$, when the surface are just touching under a very light load conditions to zero if the mean planes coincide exactly; a condition that is very unlikely to occur even under relatively high contact pressures for soft surfaces pressed together (O'Callaghan, 1973). Therefore for a lightly loaded contact the mean thickness of the gas gap can be estimated as equal to $3\sigma$.

Antonetti (1992) obtained an equation for the mean separation of contacting surfaces with a Gaussian height distribution. The mathematical expression is given by equation 8.4 below:

$$\delta = 1.53\sigma \left( \frac{P}{H} \right)^{-0.097}$$

where:

- $\sigma$ = rms roughness, $\mu$m
- $P$ = contact pressure, MPa
- $H$ = microhardness of the softer of the two contacting surfaces, MPa
- $\delta$ = mean separation or mean thickness of the gas gap, $\mu$m

When heat is applied along the longitudinal axes of the contacting test specimens, their end surfaces distort due to the thermal stress caused by temperature gradients (O'Callaghan, 1987). Figure 8.2 illustrates in exaggerated form how the distortion occurs in two nominally flat contacting surfaces. The degree of influence of the distortion on the thermal conductance is not very critical for very rough contacting surfaces since the amount of distortion is only a small percentage of the mean separation. However as the surface becomes smoother its influence increases thereby making it necessary to be considered in the calculation.

Using the nomenclature in figure 8.2 and considering initially (before heat is applied) flat contacting surfaces, the magnitude of the interfacial gap due to distortion (as heat is applied) is calculated. The derivations for the radius of curvature $\rho$ is presented in many literature (e.g. Madhusudana, 1996) and is computed as
\[ \rho = \frac{k_1}{\alpha_1 q} \]  

where \( k_1 \) is the thermal conductivity of solid 1, \( \alpha_1 \) is its coefficient of linear expansion, and \( q \) the heat flux.

Referring to figure 8.2, the radius of curvature of the bottom end of the top specimen is

\[ \rho_1 = \left[ \left( \sqrt{\rho^2 - r_0^2} - L \right)^2 + r_0^2 \right]^{\frac{1}{2}} \]

where:

\( r_0 = \) radius of the specimen

\( L = \) length of the specimen
Figure 8.2 Exaggerated representation of the thermal distortions of the contacting surfaces as a result of allowing heat to flow across the interface.
The radius of curvature $\rho_2$ is computed using an equation similar to equation 8.5 except that the thermal conductivity and coefficient of linear expansion are for solid 2.

With $\rho_1$ and $\rho_2$ known, the type of contact, i.e., either peripheral or central can be determined.

For $\rho_1 < \rho_2$ the contact is *peripheral* and the magnitude of the interfacial gap $c$ at any radial position $r$ may be expressed as

$$c = \sqrt{\rho_1^2 - r^2} - \sqrt{\rho_2^2 - r^2} - \sqrt{\rho_1^2 - r_0^2} + \sqrt{\rho_2^2 - r_0^2}$$  \hspace{1cm} 8.7

For $r = 0$ the interfacial gap is maximum and can be computed using the equation below:

$$c_{\text{max}} = \rho_1 - \rho_2 + \sqrt{\rho_2^2 - r_0^2} - \sqrt{\rho_1^2 - r_0^2}$$  \hspace{1cm} 8.8

For $\rho_1 > \rho_2$ the contact is *central* and the interfacial gap $c$ at any radial position $r$ is calculated by the equation below:

$$c = \rho_2 - \rho_1 + \sqrt{\rho_1^2 - r^2} - \sqrt{\rho_2^2 - r^2}$$  \hspace{1cm} 8.9

It is maximum when $r = r_0$ as given by the following equation:
The interfacial gap \( c \) is added to the surface roughness \( \sigma \) and using equation 8.4 the mean thickness of the gap is therefore

\[
\delta = 1.53 \left( \sigma + c \right) \left( \frac{P}{H} \right)^{-0.097}
\]

Conduction heat transfer through a gas layer in between two surfaces is commonly classified into four heat flow-regimes; continuum, temperature jump, transition, and free molecular (Springer, 1971). A non-dimensional parameter called the Knudsen number characterises the type of heat flow regime. It is defined as follows:

\[
N_{Kn} = \frac{\lambda}{\delta}
\]

where the symbols are as defined previously.

The type of heat flow regime is identified based on the value of the Knudsen number:

1) Continuum: \( N_{Kn} << 1 \); the Fourier's law of heat conduction may be applied.
2) Temperature Jump: \( 0.01 < N_{Kn} < 0.1 \); Equation 8.1 is applicable.
3) Transition: $0.1 < N_{Kn} < 10$; intermolecular collisions and the energy exchange between the gas molecules and the surfaces are both important. Equation 8.1 is applicable.

4) Free Molecular Conduction: $N_{Kn} > 10$; in this case, the mean gap thickness would be much smaller than the temperature jump distances, and equation 8.1 may be approximated as

$$h_g \approx \frac{k_g}{g_1 + g_2}$$  \hspace{1cm} 8.13

8.2 Thermal Insulation of the Heat Flux Meters and Test Specimens

One of the most important requirements in thermal contact conductance experiment of coaxial cylinders is to maintain the axial heat flux as it flows from one test specimen to the other. This means elimination or minimisation of the radial heat losses. Radial heat losses are due mainly to conduction and radiation. At moderate temperatures (less than 300°C) and short test specimens (25mm in length), radiation losses are negligible. Radial heat loss due to conduction is eliminated in experiments under vacuum. However for experiments with gas in between the contacting surfaces, the chamber (previously called the vacuum chamber) is filled with gas thereby allowing heat to flow radially. This radial heat flow should be minimised and insulating the heat flux meters and the test specimens does this.

There are three layers of thermal insulation used in the experiments. The first layer is made of teflon material. The thermal conductivity of teflon is 2.3 W/mK and can withstand to temperatures up to 260°C. It is used because it can be machined precisely to the dimensions that are needed to ensure that the heat flux meters and test specimens are always aligned. It is slippery thus allowing the heat flux meters and test specimens to slide freely along their longitudinal axes. Its texture is not powdery thereby eliminating the possibility
of dust contamination in the contact. It has slots to allow the passage of the thermocouple wires. It is cylindrical in shape and split in two halves.

The second layer is glass wool. Its thermal conductivity is 0.038 W/mK. It is inserted in the annulus formed between the teflon insulation and the third layer insulator. Its texture (hairy) allows it to be inserted in the slots for the thermocouple wires thereby minimising heat leaks.

The third layer is Kaowool wet felt. It is Kaowool fibre blanket treated with colloidal silica. Its thermal conductivities at 100°C, 150°C, 200°C and 250°C are 0.0565, 0.0583, 0.0612, and 0.0651 W/mK respectively. The material as received is flexible and does not contain an organic binder that may contaminate the environment inside the chamber. The material as received from the supplier is in sheet form of thickness around 25 mm. It is wet, flexible, compressible and can be stripped into thinner sheets. It becomes a little bit harder and decreases its flexibility when dried. These properties would make moulding the material to the required shaped possible. The third layer of insulation was made by stripping thin sheets of the wet felt then cutting each sheet to the right size. Each sheet is wrapped around a tube with an outside diameter of around 56 mm. Six sheets one on top of the other were wrapped around the tube. The sheets were wrapped in such a manner that their ends would meet forming a thin slot along the axis of the tube. The wrapping of the six sheets resulted to a cylinder of around 56mm inside diameter, 80mm height and 26 mm thick with a thin slot that was formed as the ends met. It is then wrapped with masking tape in order to hold the sheets together and with the tube was placed in an oven maintained at 70°C. It was allowed to stay in the oven for 30 hours. The tube was then pulled out and the result is an insulator in cylindrical shape with slot. It is dry, harder but has still some degree of flexibility. The slot can be widened or closed by flexing. This made the placement of the thermocouple wires during installation easy. Figures 8.3 and 8.4 show the assembled thermal insulations in different views.
Metal strip for clamping

Teflon

Glass wool

Kaowool

Thermocouple wires going to the U-tube

Figure 8.3 Diagram of the Thermal Insulator (Cross-Section)
Figure 8.4 Diagram of the Thermal Insulator (Top View)
The thermal insulation should be installed according to the following procedures:

1) Place the heat flux meters and test specimens on one-half of the teflon insulator. The insulator should be in horizontal position.

2) Arrange the thermocouple wires to the slots provided for them.

3) Cover the assembly of heat flux meters and test specimens with the other half of the teflon insulator.

4) Mount the teflon insulator (with the heat flux meters and test specimens inside) in the chamber.

5) Install the Kaowool insulator by sliding it from the top. Flex the slot wider in order to accommodate the thermocouple wires while sliding.

6) When the Kaowool blanket insulator is already in place, a metallic strip that is formed into a ring is used to close the slot. Two rings are placed; one is wrapped on the lower part of the insulator while the other is on the upper.

7) The glass wool is then inserted into the annulus formed between the teflon and Kaowool insulator using a specially shaped wire. The thermocouple wires must not be moved during the insertion of the glass wool. The insertion of the glass wool is stopped only if it is compact enough.

8.3 Experimental Procedure

The experiments were performed at a constant low-contact pressure. When everything had been installed; thermocouple wires, heat flux meters and test specimens, the experiment was conducted using the following steps:

1) The chamber is evacuated using the vacuum pump.

2) Heat is applied. Then temperature readings and thermal contact conductance are determined once the temperature has stabilised.

3) The heat flux is increased by adjusting the voltage using the VARIAC. Then step no. 2 is repeated.
4) Several readings are done thereby getting thermal contact conductance and mean temperature results.

5) From the above results the thermal conductivities (expressed as function of the temperature) of the test specimens are determined using the method outlined in section 5.2.1 of chapter 5. The purpose of determining the thermal conductivities is that in the experiments with gas, the heat flux flowing through the contact is to be determined using the test specimens as the heat flux meters. This would result in a more accurate estimate of the contact conductance.

6) The gas is introduced into the chamber. The vacuum pump is still running for few seconds while introducing the gas. The purpose is to evacuate the undesirable gas that initially occupies the gas line from the tank to the chamber. The gas pressure should be slightly higher than atmospheric. This ensures that if there is a leak the gas is flowing out instead of air flowing in thus preventing the mixing of the gas and outside air.

7) Several readings are then taken at different heat flux and mean junction temperature.

8) The heater and cooler are switched off.

9) The chamber is again evacuated.

10) Another type of gas is introduced into the chamber

11) Step no. 7 onward is repeated. The number of repetitions depends on the number of types of gases used for a particular pair of test specimens.

12) The heater and cooler are then switched off in preparation for dismantling.

13) A new pair of test specimens are installed.

14) All steps from no. 1 onward are repeated.

8.4 Experimental Results and Discussion

Three pairs of test specimens were used in the experiments; two pairs of stainless steel SS 304 and aluminium Al 6060 materials, and one pair of SS
304 and NILO 36 materials. The gases used in the experiments using the pair of SS 304 and Al 6060 are helium, argon, nitrogen and air. While only helium, argon and air were the gases used for the SS 304 and NILO 36 pair. The contact pressure is 95 kPa. The contact pressure fluctuated slightly with chamber pressure. The fluctuation was very small (approximately 0.5 kPa) and was neglected in the calculation that for all experiments done the contact pressure was considered to be a constant.

Pair 1: Material: SS 304 and Al 6060; Specimens: S18 and A27

The surface characteristics and relevant thermophysical properties of the test specimens are given below:

<table>
<thead>
<tr>
<th>Roughness, ( \sigma ) in microns</th>
<th>Slope, ( m ) in radians</th>
<th>Coefficient of linear expansion, ( \alpha ) in m/m(^\circ)C</th>
<th>Thermal conductivity, ( k ) in W/m-K (( T ) in degree Celsius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 304/S18 3.5500</td>
<td>0.5716</td>
<td>0.0000172</td>
<td>10.536 + 0.11T – 2.13E-4T(^2)</td>
</tr>
<tr>
<td>Al 6060/A27 0.5336</td>
<td>0.3968</td>
<td>0.0000236</td>
<td>179.17 + 0.293 T</td>
</tr>
<tr>
<td>Effective Value 3.5898</td>
<td>0.6958</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The effective value indicated in the above table is computed as the square root of the sum of squares. The aluminium specimen (A27) of the pair has a very smooth surface. Note that the thermal conductivity equation for the stainless steel specimen is not linear. This is because the experiments were conducted over a broader range of temperature (from 25°C to 170°C) and, therefore a linear equation was not sufficient. In the experiments with gas the test specimens were used for the heat flux calculation because as mentioned earlier the heat loss from the top heat flux meter to the bottom heat flux meter is higher compared with from one specimen to the other. The sufficiency of the thermal conductivity equation in solving the heat flux was constantly monitored and found to be always in between the readings of the top heat flux meter and bottom heat flux meter.
The results of the experiments plotted as total thermal conductance against the heat flux are shown in figure 8.5. The total thermal conductance, \( h_t \), is the sum of the gas gap conductance, \( h_g \), and solid spot conductance, \( h_c \). The solid spot conductance was obtained by the experiments in vacuum. Therefore the gas gap conductance can be determined as:

\[
h_g = h_t - h_c \tag{8.14}
\]

The following are observed from the experimental results:

1) In the vacuum environment the results have trends that are similar to the results observed from experiments on thermal rectification for similar and dissimilar materials (discussed in chapter 6). The total conductance tends to increase as the heat flux increases. This is expected because the conductance is directly proportional to the harmonic mean of the thermal conductivities of the specimens and it (harmonic mean of the thermal conductivities) increases with increase in temperature.

2) With gas the relative values of the total thermal contact conductance depend largely on the variation of the gas thermal conductivity. As expected the values of the total thermal conductance with gas are higher than in vacuum. As was seen in Table 8.1, argon has the lowest thermal conductivity, air and nitrogen are near each other and higher than argon, and helium has the highest. The results confirm that the total thermal conductance is highest with helium gas, followed by nitrogen and air, and the lowest is with argon gas in the whole heat flux range.

3) The trend of the total thermal conductance with respect to the heat flux for the S18 to A27 direction of heat flow is slightly going upward (for low to medium range of heat flux) then it slowly goes downward (for medium to high heat flux range) for all gases. For the A27 to S18 direction of heat flow and with helium the total thermal conductance is
almost constant (with slight fluctuation) throughout the heat flux range; for nitrogen there is a very slight increase (from low to medium heat flux range) then slight decrease afterwards; there is no clear trend for air but instead it is slightly fluctuating; and for argon it slightly fluctuates in the low to medium heat flux range then decreases afterwards.

A theoretical calculation of the gas gap conductance was done using the equations and gas properties presented in section 8.1. The value of the interfacial gap, c, due to the distortion of the contacting surfaces used in the calculation is based on the maximum. A computer program was generated to facilitate the computation (see appendix D for the computer program flow chart). The results were then compared with the experimental results. The experimental results for the gas gap conductance were obtained by using equation 8.14, i.e., subtracting the solid spot conductance from the total thermal conductance. Figures 8.6, 8.7, 8.8, and 8.9 present the comparison of the results of the theoretical calculation and the experiments. The theoretical values in all cases are close to the experimental values. The following are observed when comparing the theoretical and experimental results:

1) Helium Gas (Figure 8.6)

For the S18 to A27 direction of heat flow, both the theoretical and experimental values of the gas gap conductance tend to slightly decrease as the heat flux increases. The theoretical calculation is slightly underpredicting. The slight underprediction decreases as the heat flux increases.

For the A27 to S18 direction of heat flow, the theoretical results are slightly decreasing while the experimental results are slightly increasing as the heat flux is increased.

2) Nitrogen Gas (Figure 8.7)

For the S18 to A27 direction of heat flow, both the theoretically calculated and the experimental values exhibit decreasing trends as the heat flux increases. The rate of decrease of the experimental values is higher than the theoretical.
For the A27 to S18 direction of heat flow, both the theoretically calculated and experimental values decrease as the heat flux increases. The theoretical calculation is over predicting throughout the heat flux range.

3) Air (Figure 8.8)

For the S18 to A27 direction of heat flow, the theoretical calculation agrees well with the experimental from low to medium heat flux range. Onwards, the experimental values decrease rapidly while the theoretical values decrease slightly resulting to over prediction.

For the A27 to S18 direction of heat flow, both theoretical and experimental exhibit decreasing trends as the heat flux increases. The theoretical values over predict throughout the heat flux range.

4) Argon Gas (Figure 8.9)

For the S18 to A27 direction of heat flow, both the theoretical and experimental values exhibit decreasing trends as the heat flux increases. The rate of decrease of the experimental is higher than the theoretical.

For the A27 to S18 direction of heat flow, the theoretical and experimental values exhibit decreasing trends as the mean junction temperature increases. The theoretical calculation slightly over predicts throughout the heat flux range.
Figure 8.5 Total Thermal Conductance versus Heat Flux Plot of Specimens S18 and A27 (Experimental Results)
Experimental Results in Helium and Vacuum with Specimens: S18 and A27

(a)

Gas Gap Conductance in Helium with Specimens: S18 and A27

(b)

Figure 8.6 Conductance versus Heat Flux Plot of Specimens S18 and A27 in Helium Gas and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory.
Experimental Results in Nitrogen and Vacuum with Specimens: S18 and A27

(a)

(b)

Figure 8.7 Conductance versus Heat Flux Plot of Specimens S18 and A27 in Nitrogen Gas and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory
Figure 8.8 Conductance versus Heat Flux Plot of Specimens S18 and A27 in Air and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot - Comparison of Experiment with Theory
Experimental Results in Argon and Vacuum with Specimens: S18 and A27

Figure 8.9 Conductance versus Heat Flux Plot of Specimens S18 and A27 in Argon and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory
The surface characteristics and relevant thermophysical properties of the test specimens are given below:

<table>
<thead>
<tr>
<th></th>
<th>Roughness, ( \sigma ) in microns</th>
<th>Slope, ( m ) in radians</th>
<th>Coefficient of linear expansion, ( \alpha ) in m/m-°C</th>
<th>Thermal conductivity, ( k ) in W/m-K (( T ) in degree Celsius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 304/S15</td>
<td>3.6359</td>
<td>0.6154</td>
<td>0.0000172</td>
<td>10.536 + 0.11T – 2.13E-4T^2</td>
</tr>
<tr>
<td>AI 6060/A15</td>
<td>2.2140</td>
<td>0.4975</td>
<td>0.0000236</td>
<td>179.17 + 0.293T</td>
</tr>
<tr>
<td>Effective Value</td>
<td>4.2569</td>
<td>0.7913</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The experimental procedure is the same as for pair 1. The results of the experiments plotted as total thermal conductance against the heat flux are shown in figure 8.10. The following are observed from the experimental results:

1) The relative values of the total thermal conductance with respect to the heat flux in vacuum and with gas are similar to the previously discussed experimental results.

2) The trend of the total thermal conductance with respect to the heat flux for the S15 to A15 direction of heat flow is: going upward as the heat flux increases for helium gas; slightly going upward as the heat flux increases for Nitrogen gas; for air it is slightly decreasing as the heat flux is increasing from low to medium range then slightly increasing onwards; for argon the trend is slightly increasing.

For the A15 to S15 direction of heat flow and with helium the total thermal conductance is increasing; for nitrogen it slightly decreases...
first then it increases slowly afterwards; the trend for air and argon is increasing as the heat flux increases.

Figures 8.11, 8.12, 8.13, and 8.14 show the comparison of the theoretical and experimental values of the gas gap conductance. The theoretical values are obtained using the same procedure applied to pair 1. The theoretical values are relatively close to the experimental values. The following are observed from the figures:

1) Helium Gas (Figure 8.11)

For S15 to A15 direction of heat flow the trend of the experimental values is moderately increasing while the theoretical is slightly decreasing as the mean junction temperature is increasing.

For A15 to S15 direction, the theoretical values are slightly decreasing while the experimental are slowly increasing.

2) Nitrogen Gas (Figure 8.12)

For S15 to A15 direction of heat flow the trend of the experimental values is slightly increasing while the theoretical is slowly decreasing as the heat flux is increasing.

For A15 to S15 direction, the theoretical values are slowly decreasing throughout the heat flux range while the experimental are decreasing at first then very slightly increasing onward.

3) Air (Figure 8.13)

For the S15 to A15 direction of heat flow the experimental values are slowly decreasing as heat flux increases from low to medium range then it slightly increases afterwards. The trend of theoretical values is decreasing as the heat flux is increasing.

For the A15 to S15 direction the theoretical is slightly decreasing whereas the experimental is increasing as the heat flux is increasing.

4) Argon Gas (Figure 8.14)

For the S15 to A15 direction of heat flow the experimental values are decreasing as the heat flux is increasing from low to medium range
and then increasing afterwards. The theoretical values continuously decrease with increase in heat flux.

For the A15 to S15 the experimental and the theoretical values have a similar trend of slightly decreasing as the heat flux is increasing. However the theoretical values slightly overestimate the conductance throughout the heat flux range.
Figure 8.10 Total Thermal Conductance versus Heat Flux Plot of Specimens S15 and A15 (Experimental Results)
Experimental Results in Helium and Vacuum with Specimens: S15 and A15

(a)

Figure 8.11 Conductance versus Heat Flux Plot of Specimens S15 and A15 in Helium and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory
Figure 8.12 Conductance versus Heat Flux Plot of Specimens S15 and A15 in Nitrogen and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot-Comparison of Experiment with Theory
Experimental Results in Air and Vacuum with Specimens: S15 and A15

(a)

Gas Gap Conductance in Air with Specimens: S15 and A15

(b)

Figure 8.13 Conductance versus Heat Flux Plot of Specimens S15 and A15 in Air and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory
Figure 8.14 Conductance versus Heat Flux Plot of Specimens S15 and A15 in Argon and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory
Pair 3: Material: SS 304 and NILO 36; Specimens: S24 and N5

The surface characteristics and relevant thermophysical properties of the test specimens are given below:

<table>
<thead>
<tr>
<th>Roughness, $\sigma$ in microns</th>
<th>Slope, $m$ in radians</th>
<th>Coefficient of linear expansion, $\alpha$ in m/m°C</th>
<th>Thermal conductivity, $k$ in W/m-K (T in degree Celsius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 304/S24</td>
<td>3.6936</td>
<td>0.5962</td>
<td>$10.536 + 0.11T - 2.13E^{-4}T^2$</td>
</tr>
<tr>
<td>NILO 36/N5</td>
<td>5.4559</td>
<td>0.6028</td>
<td>$14.066 + 0.00553 T$</td>
</tr>
<tr>
<td>Effective Value</td>
<td>6.5886</td>
<td>0.8478</td>
<td></td>
</tr>
</tbody>
</table>

The experimental procedure is the same as for pairs 1 and 2. The results of the experiments plotted as total thermal conductance against the heat flux are shown in figure 8.15. The following are observed from the experimental results:

1) The relative values of the total thermal conductance with respect to the heat flux in vacuum and with gas are similar to the previously discussed experimental results using the pairs S18/A27 and S15/A15.

2) The trend of the total thermal conductance with respect to the heat flux for the S24 to N5 direction of heat flow is: very slightly decreasing with helium gas; slightly increasing as the heat flux is increasing with air; and slightly decreasing with increasing heat flux for argon.

For the N5 to S24 direction of heat flow the total thermal conductance with helium gas is decreasing as the heat flux is increasing; with air it is slightly increasing throughout the heat flux.
range; and with argon gas it is increasing as the heat flux is increasing.

The theoretical values of the gas gap conductance are computed using the same computer program used to pairs 1 and 2. In this particular pair of specimens the equation by Antonetti (1992) failed to predict well. However, the mean thickness $\delta$ of the gas gap can be calculated as

$$\delta = 3\sigma + c$$  

where $\sigma$ is the effective roughness of the contacting surfaces and $c$ is the interfacial gap due to the distortion of the contacting surfaces as heat is applied and can be computed using equations 8.7 to 8.10. The value $3\sigma$ is based on the discussion presented in section 8.1, i.e., for a randomly rough surface, 99.3% of the surface heights lie within the 3 standard deviations or $3\sigma$ (O'Callaghan, 1973).

Figures 8.16, 8.17 and 8.18 show the comparison of the theoretical and experimental values of the gas gap conductance. The good agreement between theory and experiment may be noted. The following are observed from the figures:

1) Helium Gas (Figure 8.16)

For S24 to N5 direction of heat flow the experimental values of the gas gap conductance is very slightly decreasing as the heat flux is increasing. The theoretical values are under predicting slightly and tend to increase very slowly as the heat flux increases.

For the N5 to S24 direction of heat flow the experimental values are slightly decreasing as the heat flux is increasing. The theoretical values are under predicting slightly and are slowly increasing as the temperature is increasing.

2) For Air (Figure 8.17)

For the S24 to N5 direction of heat flow the experimental values of the gas gap conductance are moderately increasing as the heat flux is
increasing. The theoretical values are slightly increasing throughout the heat flux range.

For the N5 to S24 direction of heat flow both the theoretical and experimental values are increasing as the heat flux is increasing.

3) For Argon Gas (Figure 8.18)

For S24 to N5 direction of heat flow the experimental values are very slowly increasing first then decreasing afterwards. The theoretical values are slowly increasing as the heat flux is increasing.

For the N5 to S24 direction of heat flow the trends of the theoretical and experimental values are very similar.
Figure 8.15 Total Thermal Conductance versus Heat Flux Plot of Specimens S24 and N5 (Experimental Results)
Figure 8.16 Conductance versus Heat Flux Plot of Specimens S24 and N5 in Helium and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot-Comparison of Experiment with Theory
Figure 8.17 Conductance versus Heat Flux Plot of Specimens S24 and N5 in Air and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory
Experimental Results in Argon and Vacuum with Specimens: S24 and N5

(a)

Gas Gap Conductance in Argon with Specimens: S24 and N5

(b)

Figure 8.18 Conductance versus Heat Flux Plot of Specimens S24 and N5 in Argon and Vacuum Environment. (a) Total Thermal Conductance vs. Heat Flux Plot (b) Gas Gap Conductance vs. Heat Flux Plot—Comparison of Experiment with Theory
8.5 General Discussions of the Results

The main factors affecting gas gap conductance are gas thermal conductivity, mean thickness of the gas gap, and temperature jump distance. The temperature jump distance is dependent on the properties of the gas, notably the accommodation coefficient, ratio of specific heats, thermal conductivity of the gas, gas viscosity, gas specific heat at constant volume, and the mean free path of the gas molecules. Almost all of them, to varying degrees, are temperature dependent.

Previous works on gas gap conductance do not mention about the effect of contact surface distortion on gas gap conductance. However the incorporation of the interfacial gap due to distortion in the theoretical calculation gives result that could help in explaining the downward trend of the gas gap conductance experimental values with heat flux. It must be noted that distortion is dependent on the heat flux as given in equation 8.5

The theory presented in this thesis on gas gap conductance is capable of doing quantitative evaluation. The formulas for the calculation of the mean thickness however, are not generally applicable. In the theoretical calculation the formula of Antonetti (equation 8.4) gives a better results for pairs 1 and 2. But for pair 3 it is equation 8.14 that gives a better result. The results for all experiments show that the theoretical values agree well with the experimental values. However, with regards to the directional effect on gas gap conductance it can be said that the present theories are not sufficient to predict the correct trend. Prediction of thermal rectification of dissimilar metals in an environment with gas is difficult at the moment. The following factors are recognised to affect the gas gap conductance but at present are not well understood, not precisely measured or there are not enough data:

1) Thermal accommodation coefficient

Thermal accommodation coefficient is already well defined and had been studied since the 1930’s (Roberts, 1930; Michels, 1932; Mann, 1934; Raines, 1939; Thomas and Olmer, 1943; Wiedmann, 1946; Thomas and Golike, 1954; Wachman, 1962; Kharitonov, 1973;
Ullman, 1974; Song, 1987). However results show that the variation of the values is very large even for the same gas in contact with the same materials with different surface finish. In short the available data are only accurate for the particular case studied. There is no existing formula or correlation that can accurately calculate the thermal accommodation coefficient as functions of the properties of the gas, thermophysical properties and surface characteristics of the surface in contact with the gas and temperature, i.e. there is no method available by which one can predict the thermal accommodation coefficient for all possible solid /gas combinations.

2) Precise three-dimensional profile of the contacting surfaces

It has been shown in the theoretical calculation that surface distortion affects the gas gap conductance. The calculation presented is applicable only to nominally flat surfaces. Accurate determination of the distortion requires a precise three-dimensional profile of the contacting surfaces. For an accurate calculation of the surface distortion factors like the wavelengths and amplitude of the surface waviness in three dimensions are required.
CHAPTER 9
CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

9.1 Conclusions

The work described in this thesis includes the design and fabrication of the apparatus used for the experimental part of the research work. The design can be considered unique because it has some features that are completely different from the axial heat flow cut bar type of apparatus used by other researchers. Assembly and disassembly of the test specimens and thermal insulator (for gas gap conductance experiments) are easy. The data acquisition system of the apparatus is assembled using data acquisition modules that are readily available. A computer program was developed that can automatically process the thermocouple readings into the desired results. The accessories, parts and materials are available in Australia except for the material for the heat flux meter that was obtained from the National Institute of Standards and Technology of the United States of America. The performance of the apparatus used for the experimental work was found to be very satisfactory in terms of accuracy and reliability. Its design and unique features are considered to be improvements over that with the existing conventional types of rigs.

The specific areas on thermal contact conductance presented in this thesis are the following:

1) Thermal rectification of similar and dissimilar metals under vacuum
2) Effect of metallic foils on thermal contact conductance
3) Directional effect on gas gap conductance

Thermal Rectification of Similar and Dissimilar Metals under Vacuum

A theory that explains the effect of heat flow direction on thermal contact conductance of similar and dissimilar metals in a vacuum environment was presented. It is based on the assumptions that the asperities of the contacting
surfaces are spherically shaped and that the contacting surfaces are nominally flat. The radius of the asperity is expressed as a function of the surface roughness and slope. With the radii of contacting asperities known, the contact area is calculated using the Hertz equation for two contacting spheres. The contacting asperities are subjected to different temperatures as the heat flow is reversed. This leads to expansion or shrinkage of the contacting asperities as the heat flow direction is reversed. The result is a change in the radii of the contacting asperities. The contact area is then calculated with considerations of the changes of the radii. The change in the contact area is then incorporated in the calculation of the thermal contact conductance. In the calculation of the thermal contact conductance the dependency of the thermal conductivities of the test specimens to temperature and the effect of oxide layer, if any, are also considered. A computer program that calculates the thermal contact conductance for both directions of heat flow at different heat flux and contact pressure was generated.

The computer simulation shows the following:

1) For similar materials there is a higher thermal contact conductance (positive thermal rectification) if the direction of heat flow is from a specimen with a surface of smaller radius of asperities to a specimen with a surface of larger radius of asperities compared with the opposite direction.

2) For similar materials there is no change of thermal contact conductance as the heat flow is reversed if the radii of the contacting asperities are equal.

3) For dissimilar materials the change of the thermal contact conductance as the direction of heat flow is changed is affected not only by the change of the radii of the contacting asperities but also of the change of the thermal conductivities of the test specimens due to variation in temperature.

4) The effect of aluminium oxide is significant at high contact pressure. At low contact pressure the resistance to the heat flow due to the aluminium oxide is relatively small compared with the contact
resistance. As the contact pressure is increased the contact resistance decreases faster than the resistance due to the oxide. This makes the resistance due to the aluminium oxide significant at high contact pressure.

The theory was verified in the macroscopic level by conducting an experiment using a pair of test specimens of similar materials where one has a very smooth spherical end in contact with the very smooth flat end of the other. The experimental results show a higher thermal contact conductance throughout the whole range of contact pressure if the direction of heat flow is from the spherical end to the flat end. In the microscopic level the experimental results in general agree well with the theoretical calculation.

**Effect of Metallic Foils on Thermal Contact Conductance**

The experimental results show that the thermal contact conductance increases with increase in contact pressure regardless of whether the joint is bare or filled. The aluminium and gold foils used as interstitial materials enhanced the thermal contact conductance. The experimental results indicate the existence of an optimum foil thickness for a particular effective roughness of the contacting surfaces.

An explanation of the mechanism of the contact of two surfaces with a metallic foil inserted in between was presented. For relatively thick metallic foil the resistance to the flow of heat is considered as the sum of the two contact resistances and the bulk resistance of the foil. A numerical calculation based on this was done and the results agree well with the experimental results. In the calculation, the effect of the aluminium oxide (if aluminium foil is used) is considered. The calculation for thin metallic foil is considered a different case since the tearing of the foil resulting to a substrate to substrate contact in the torn portion and the possible bending and warping of the foil should be taken into account.
Directional Effect on Gas Gap Conductance

Present theories on gas gap conductance indicate that (gas gap conductance) is independent of the heat flux. In this study the distortion of the contacting surface is incorporated in the present equations for the calculation of gas gap conductance. The surface distortion is dependent on the heat flux, thus making the gas gap equation heat flux dependent.

The experimental results show that gas gap conductance is dependent of heat flux although it is not as strong as other factors like the thermal conductivity of the gas. They agree well with the theoretical calculation. However with regards to the directional effect the trends of the experimental values are not accurately predicted by the theory. It is concluded that the directional effect maybe more accurately predicted once there is sufficient data available for parameters such as thermal accommodation coefficients and accurate correlations regarding effective gap width.

Microhardness of the Contacting Surfaces

The microhardness of rough surfaces can not be directly measured using the conventional indentation method. The size of the indentation is of the same order of magnitude to the roughness of the surface. It is very difficult to identify and measure the indentation on a rough surface. A correlation for the determination of the microhardness of a surface was obtained. It is expressed in terms of the rms roughness and rms slope of the surface. The coefficients and exponents of the correlations were obtained by plotting the microhardness and indentation as measured by a microhardness tester of the smooth end of the test specimen. The correlation was then used in the theoretical calculation of the thermal contact conductance.
9.2 Suggestions for Future Works

This thesis has led to the following ideas that are suggested for future works:

1) There is a need for more experimental work on the natural growth of aluminium oxide on surfaces with roughness from 0.500μm to 6.000μm at room conditions. At present, the available data are not representative of the actual conditions and could only give an approximation to the thickness of oxide film.

2) Theoretical work on the determination of the thermal contact conductance with metallic foil insert with consideration of the warping and bending of the foil.

Although there are several number of theoretical and experimental works on the effect of interstitial materials on thermal contact conductance at present, there is no theoretical work that take into account the effect of the warping and bending of the foil. There is a need to formulate an index number that would indicate the occurrence of warping and bending. This is a case between the following extremes:

a) Very thick metallic foil where the thermal contact resistance is the sum of two contact resistances and the bulk resistance of the foil and;

b) Relatively thin metallic foil where substrate to substrate contact happens due to tearing of some portions of the foil.

3) Experimental and theoretical works on the determination of the thermal accommodation coefficient for a particular gas in conditions that are similar in thermal contact conductance experiment, i.e., similar surface characteristics, surface material, and temperature.

At present, the thermal accommodation coefficient used in the calculation may not be representative of the actual conditions. Experimental results of many researchers show that even for similar gas and surface materials, the thermal accommodation coefficient varies by a large range due to change in the surface finish, its cleanliness, etc.
4) Theoretical and experimental works on the effect of direction on gas gap conductance with dissimilar specimen materials.

For the theoretical work emphasis can be given on the effect of surface distortion (due to the application of heat) on the mean thickness of the gas gap. Present formulas on for the calculation of the mean thickness of the gas gap are only accurate (as validated by the experimental results) for a particular range of roughness. Gas gap conductance is very sensitive to the mean thickness of the gas gap and distortion apparently contributes much specially in cases where the contacting surfaces are very smooth. In the experimental part, the surface analysis of the test specimen should not only include the roughness, slope, peak height but also the amplitude and wavelength of the surface waviness.

5) Experimental and theoretical works of the dependency of surface microhardness and the modulus of elasticity on temperature.

These two factors are major parameters in the calculation of thermal contact conductance. The need to know their dependency on temperature is very important in thermal rectification investigation. This is because thermal rectification (positive or negative) refers mainly the change of thermal contact conductance as the direction of heat is reversed. The reversal of the direction results to a temperature change and corresponding change in the thermophysical properties of the test specimens. The change in the thermophysical properties may lead to a change in thermal contact conductance. This effect is in addition to the change in contact area brought about by differential expansion at its interface.

6) Experimental works on new methods of surface analysis.

At present the usual method of determining the surface profile parameters is by the used of a surface analyser. The surface analyser has a diamond stylus that traces the surface and then it amplifies and processes the readings. Several readings have to be done for each surface in order to determine the surface profiles. The tracing process scratches the surface and may change or alter the surface finish. This is
very evident in softer materials like aluminium. The size of the stylus is also a limitation in the tracing process. Cases may happen where the depth of the crevice is not accurately measured because the stylus is too big.

There is a need to experiment on methods that do not need physical contact in order to determine the surface profiles. One method that can be explored is by the use of optical instruments in surface profile analysis.

7) Experimental works on thermal rectification of similar materials under vacuum or with gas environment using specimens of the same diameter but of different lengths.

Experiments on the variation of gas gap conductance with the mean junction temperature can be done by:

a) Use of test specimens of equal lengths but of very different thermal conductivities;

b) Use of test specimens of similar materials but of different lengths.

The above methods can vary the mean junction temperature by reversing the direction of heat flow. Method (b) has not been used in past experiments and is expected to give further insights on the directional effect on gas gap conductance.
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APPENDIX A
DERIVATION OF THE AREA COEFFICIENT OF THERMAL EXPANSION

The coefficients of thermal expansion of metals that are available in the literature are usually expressed in terms of unit length per unit length per temperature unit. In the calculation of the area thermal expansion the area coefficient of thermal expansion is needed. The area coefficient of thermal expansion can be expressed as function of the linear coefficient of thermal expansion. The relationship is given below:

\[ \beta = 2 \alpha \quad (m^2/m^2\cdot{}^\circ{}C) \quad \text{A.1} \]

To express \( \beta \) in terms of \( \alpha \), the following derivation is shown:

From the above figure, the area before heating is

\[ A = xy \]

Once heated the area has expanded to \( A + \Delta A \) where

\[ A + \Delta A = (x + \Delta x)(y + \Delta y) \]

Expanding the right side of the equation

\[ A + \Delta A = xy + x\Delta y + y\Delta x + \Delta x\Delta y \]
Neglecting small quantities of second order or higher and knowing that $A = xy$ and $\Delta A = \beta \Delta T$ the equation becomes:

$$xy + \beta xy \Delta T = xy + x\Delta y + y\Delta x$$

Since $\Delta y = \alpha y \Delta T$ and $\Delta x = \alpha x \Delta T$ then

$$xy + \beta xy \Delta T = xy + x\alpha y \Delta T + y\alpha x \Delta T$$

Therefore,

$$\beta = 2\alpha$$
The uncertainty analysis is based on the method presented by Kline and McClintock (1953). Let $\mathbf{R}$ be the desired result of the experiment and that it is a function of the independent variables $x_1, x_2, x_3, \ldots, x_n$, thus

$$\mathbf{R} = \mathbf{R}(x_1, x_2, x_3, \ldots, x_n) \quad \text{B.1}$$

Let $w_R$ be the uncertainty in the result and $w_1, w_2, \ldots, w_n$, be the uncertainties in the independent variables. Assuming that the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the results having these odds is given as

$$w_R = \left[ \left( \frac{\partial \mathbf{R}}{\partial x_1} w_1 \right)^2 + \left( \frac{\partial \mathbf{R}}{\partial x_2} w_2 \right)^2 + \cdots + \left( \frac{\partial \mathbf{R}}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad \text{B.2}$$

The result that is of interest in the experiment is the thermal conductance, $h$. It is a function of the heat flux and the temperature drop at the junction, $\Delta T$. It is expressed in equation form as shown below:

$$h = \frac{q}{\Delta T} \quad \text{B.3}$$
Applying equation B.3 to B.2 the uncertainty of the thermal contact conductance is as given below:

\[
\begin{align*}
    w_n = & \left[ \left( \frac{\delta h}{\delta q} w_q \right)^2 + \left( \frac{\delta h}{\delta \Delta T} w_{\Delta T} \right)^2 \right]^{\frac{1}{2}} \\
\end{align*}
\]

B.4

where:

- \( w_q \) = heat flux uncertainty
- \( w_{\Delta T} \) = temperature drop uncertainty
- \( \delta h/\delta q = 1/\Delta T \)
- \( \delta h/\delta (\Delta T) = -q(\Delta T)^2 \)

### a) Heat Flux Uncertainty Calculation

The heat flux can be calculated using the one-dimensional Fourier's equation for heat conduction. The equation is expressed as

\[
q = -k \frac{dT}{dx} 
\]

B.5

For the heat flux meter, the thermal conductivity is given by the equation

\[
k = 109.96 e^{-0.0012T} 
\]

B.6
where \( k \) is in W/mK and \( T \) in degree Kelvin

Plugging in equation B.6 into equation B.5 and integrating from \( a \) to \( b \) the result is

\[
q = \frac{109.96}{0.0012a} \left( e^{-0.0012T_a} - e^{-0.0012T_b} \right) \quad \text{B.7}
\]

The maximum error in the heat flux calculation occurs if the thermocouple junctions are getting the temperature readings from locations as shown in figure B.1. The error is maximum if the following cases occur:

**Case 1 (Upper Bound)**

The reading of thermocouple no. 1 is based on a distance 0.0003m to the right of the hole centre; at the hole centre for thermocouple no. 2; and 0.0003m to the left for thermocouple no. 3. From the figure the temperature readings in this case are \( T'_1, T'_2, T'_3 \).

**Case 2 (Lower Bound)**

The reading of thermocouple no. 1 is based on a distance 0.0003m to the left of the hole centre; at the hole centre for thermocouple no. 2; and 0.0003m to the right for thermocouple no. 3. From the figure the temperature readings in this case are \( T''_1, T''_2, T''_3 \).

From figure B.1 the temperatures \( T_1, T_2, \) and \( T_3 \) are the readings at the centre of the hole (without error due to off-centred location of the thermocouples). It must be noted that \( T_2, T'_2, T''_2 \) have the same values because they are all taken at the centre of hole no.2.
Figure B.1 Variation of Temperature with Distance
A value of 35,154 W/m² and $T_0 = 460.9$ K are used for the calculation. The values are obtained from one of the experiments using stainless steel as the specimen material.

Using equation B.6 and with $x_1$, $x_2$, $x_3$, $x_4$ equal to 0.0055m, 0.0125m, 0.0195m, 0.025m respectively, the following were calculated:

$T_1 = 457.8$ K
$T_2 = 454.0$ K
$T_3 = 450.1$ K
$T_4 = 447.1$ K

**Lower bound heat flux (Case 1)**

Using the same procedure with $x'_1$, $x'_2$, and $x'_3$ equal to 0.0058m, 0.0125m, 0.0192m respectively, the following temperatures based on case 1 (as discussed previously) are calculated:

$T_1' = 457.7$ K
$T_2' = 454.0$ K (same as $T_2$)
$T_3' = 450.3$ K

Linearising the above three readings using the method of least square, the following equation is obtained:

$T = -527.5986x + 460.5643$

Substituting $x = 0.00m$ and $x = 0.025m$ respectively,

$T_0' = 460.6$ K
$T_4' = 447.4$ K

The lower bound heat flux can then be calculated as
\[ q_u = \frac{109.96}{(0.0012 \times 0.025)} \left( e^{-0.0012(447.3743)} - e^{-0.0012(460.5643)} \right) \]

\[ = 33,648 \text{ W/m}^2 \]

**Upper bound heat flux (Case 2)**

Using the same procedure presented above, the following temperatures are obtained:

- \( T_1'' = 458.0 \text{ K} \)
- \( T_2'' = 454.0 \text{ K} \) (same as \( T_2, T_2' \))
- \( T_3'' = 450.0 \text{ K} \)

By the method of least squares a linear equation as given below is obtained:

\[ T = -574.857 \times + 461.157 \]

Using the above equation with \( x_0 = 0.000 \text{m} \) and \( x_4 = 0.025 \text{m} \) the following temperatures are calculated:

- \( T_0'' = 461.2 \text{ K} \)
- \( T_4'' = 446.8 \text{ K} \)

Therefore, the upper bound heat flux is calculated as

\[ q_u = 36,661 \text{ W/m}^2 \]
Uncertainty = \pm \frac{(q_u - q_L)}{2} = 1507 \text{ W/m}^2

Therefore,

q = 35,154 \pm 1,507

= 35,154 \pm 4.28\%

B) Uncertainty of the Temperature Drop at the Junction

The thermal conductivity of the test specimen can be expressed as

\[ k = \alpha + \beta T \]  \hspace{1cm} \text{(B.8)}

Plugging equation B.8 into the Fourier's equation for heat conduction and integrating from A to B the result is

\[-q\Delta x = \alpha T_B + \frac{\beta}{2} T_B^2 - \alpha T_A - \frac{\beta}{2} T_A^2 \]  \hspace{1cm} \text{(B.9)}

From equation B.9, \( T_B \) can be expressed as

\[ T_B = \frac{-\alpha \pm \sqrt{\alpha^2 - 2\beta \left( q\Delta x - \alpha T_A - \frac{\beta}{2} T_A^2 \right)}}{\beta} \]  \hspace{1cm} \text{(B.10)}

For the stainless steel specimen, \( \alpha = 14.602 \text{ W/m}^\circ\text{C} \) and \( \beta = 0.01232 \text{ W/m}^\circ\text{C}^2 \).

There are two cases considered in the uncertainty calculation; the upper bound case and the lower bound case.
Upper Bound Case

In this case the error due to off-centre location of the thermocouples results to the upper bound value of the junction temperature drop. The following will cause the occurrence of this case (shown in figure B.2):

1) For the top specimen, the thermocouple at location 6 (see figure B.2) is off-centred to the right by 0.0003m, the one at location 7 is exactly at the centre, and the one at location 8 is off-centred to the left by 0.0003m.

2) For the bottom specimen, the thermocouple at location 9 is off-centred to the right by 0.0003m, the one at location 10 is exactly at the centre, and the one at location 11 is off-centred to the left by 0.0003m.

The heat flux, $T_5$ (top specimen), and $T_{10}$ (bottom specimen) are given as 35,154 W/m°C, 165.1°C, and 89.85°C respectively. With equation B.10 and stainless steel top specimen the temperatures, $T_6'$, $T_7'$, $T_8'$ and $T_9'$ can be solved using $\Delta x$ equal to 0.0058, 0.0125, 0.0192 and 0.025m respectively. The values are given below:

\[
\begin{align*}
T_6' &= 152.8°C \\
T_7' &= 138.4°C \\
T_8' &= 123.9°C \\
T_9' &= 111.2°C
\end{align*}
\]

Linearising the above values with respect to $\Delta x$ the following equation is obtained:

\[
T = -2064.3 (\Delta x) + 164.154
\]
Figure B.2 Temperature – Distance Relationship of Top and Bottom Specimens (Upper Bound Value of the Junction Temperature Drop).
Using the above equation and with $\Delta x = 0.025\text{m}$, the temperature $T_9 = 112.55^\circ\text{C}$ is solved.

For bottom stainless steel specimen and with equation B.10 the temperatures, $T_{11}$, $T_{12}$, and $T_{13}$ can be solved using $\Delta x$ equal to 0.0058, 0.0125, and 0.0192m respectively. The values are given below:

\[ T_{11} = 76.81^\circ\text{C} \]
\[ T_{12} = 61.57^\circ\text{C} \]
\[ T_{13} = 46.14^\circ\text{C} \]

Linearising the above values with respect to $\Delta x$ the following equation is obtained:

\[ T = -2190.7 (\Delta x) + 88.86 \]

With $\Delta x = 0.000$, the value of $T_{10} = 88.86^\circ\text{C}$ is obtained.

Therefore the upper bound of the junction temperature drop is solved as given below:

\[
\Delta T_{\text{upper}} = \Delta T + \Delta T_{\text{top}} + \Delta T_{\text{bottom}} \\
= (T_9 - T_{10}) + (T_9' - T_9) + (T_{10} - T_{10}') \\
= (111.2^\circ\text{C} - 89.85^\circ\text{C}) + (112.55^\circ\text{C} - 111.2^\circ\text{C}) + (89.85^\circ\text{C} - 88.86^\circ\text{C}) \\
= 23.69^\circ\text{C}
\]

**Lower Bound Case**

The following will cause the occurrence of this case (as shown in figure B.3):
1) For the top specimen, the thermocouple at location 6 (see figure B.3) is off-centred to the left by 0.0003m, the one at location 7 is exactly at the centre, and the one at location 8 is off-centred to the right by 0.0003m.

2) For the bottom specimen, the thermocouple at location 9 is off-centred to the left by 0.0003m, the one at location 10 is exactly at the centre, and the one at location 11 is off-centred to the right by 0.0003m.

With equation B.10 and stainless steel bottom specimen the temperatures, $T_6^\ast$, $T_7^\ast$, and $T_8^\ast$ can be solved using $\Delta x$ equal to 0.0052, 0.0125, and 0.0198m respectively. The values are given below:

\[ T_6^\ast = 154.04^\circ C \]
\[ T_7^\ast = T_7^\prime = 138.43^\circ C \]
\[ T_8^\ast = 122.6^\circ C \]

Linearising the above values with respect to $\Delta x$ the following equation is obtained:

\[ T = -2245.7 (\Delta x) + 166.39 \]

Using the above equation and with $\Delta x = 0.025m$, the temperature $T_9^\ast = 110.25^\circ C$ is solved.

For the bottom stainless steel specimen and with equation A.10 the temperatures, $T_{11}^\ast$, $T_{12}^\ast$, and $T_{13}^\ast$ can be solved using $\Delta x$ equal to 0.0052, 0.0125, and 0.0198m respectively. The values are given below:

\[ T_{11}^\ast = 78.16^\circ C \]
\[ T_{12}^\ast = 61.57^\circ C \]
\[ T_{13}^\ast = 44.75^\circ C \]
Figure B.3 Temperature – Distance Relationship of Top and Bottom Specimens (Lower Bound Value of the Junction Temperature Drop).
Linearising the above values with respect to $\Delta x$ the following equation is obtained:

$$T = -2386.7 (\Delta x) + 91.3$$

With $\Delta x = 0.000$, the value of $T_{10} = 91.3^\circ C$ is obtained.

Therefore the lower bound of the junction temperature drop is solved as given below:

$$\Delta T_{\text{lower}} = \Delta T - \Delta T_{\text{top}} - \Delta T_{\text{bottom}}$$

$$= (T_9 - T_{10}) - (T_9 - T_9^*) - (T_{10}^* - T_{10})$$

$$= (111.2^\circ C - 89.85^\circ C) + (111.2^\circ C - 110.25^\circ C) + (91.3^\circ C - 89.85^\circ C)$$

$$= 18.95^\circ C$$

Therefore the uncertainty of the junction temperature drop is

$$\text{Uncertainty} = (\Delta T_{\text{upper}} - \Delta T_{\text{lower}})/2$$

$$= (23.69 - 18.95)/2$$

$$= 2.37^\circ C$$

The junction temperature drop is therefore

$$\Delta T_{\text{junction}} = \Delta T \pm 2.37^\circ C$$

$$= (111.2^\circ C - 89.85^\circ C) \pm 2.37^\circ C$$

$$= 21.35 \pm 2.37^\circ C$$
The overall uncertainty is computed using the following:

\[ q = h \Delta T \]

Substituting values of 35,154 W/m² and 21.35 K for \( q \) and \( \Delta T \) respectively,

\[ h = 1,646.56 \text{ W/m}^2\text{-K} \]

\[ \frac{\delta h}{\delta q} = \frac{1}{\Delta T} \]
\[ = 0.04684 \]

\[ \frac{\delta h}{\delta (\Delta T)} = -q(\Delta T)^2 \]
\[ = -77.122 \]

Therefore the uncertainty of the conductance, \( W_h \) is obtained as

\[
W_h = \left[ \left( \frac{\delta h}{\delta q} \right)^2 W_q + \left( \frac{\delta h}{\delta \Delta T} \right)^2 W_{\Delta T} \right]^{\frac{1}{2}}
\]

By substituting values that are previously calculated,

\[
W_h = \left[ ((0.04684 \times 1506.93))^2 + ((-77.122 \times 2.37))^2 \right]^{\frac{1}{2}}
\]
\[ W_h = 196 \, \text{W/m}^2\text{-K} \]

In percentage form the uncertainty of the thermal contact conductance is therefore equal to

\[ W_h = \left( \frac{196}{1647} \right) \times 100\% \]

\[ = 11.9\% \]
The heat loss due to radiation is calculated based on the data that are obtained from one of the experiments. They are the same data used in the uncertainty analysis. The heat loss that is of interest here is the radiation heat loss from the bottom end of the bottom specimen to the top end of the top specimen. The specimens are made of stainless steel. Their sides are smooth and polished.

Figure C.1 Diagram and Data for the Radiation Heat Loss Calculation
Assuming the above set-up is a case of radiation exchange between two cylindrical surfaces then the equation for the total radiation heat flow is

\[
Q = \frac{\sigma A_1 (T_1^4 - T_2^4)}{1 + \frac{A_1}{A_2} \left( \frac{1}{\varepsilon_1} - 1 \right)}
\]

where:

\( Q \) = total radiation heat flow, W

\( \sigma \) = Stefan-Boltzmann constant, 5.669 E-8 W/m\(^2\)-K\(^4\)

\( A_1, A_2 \) = area of the enclosed and enclosing surfaces respectively, m\(^2\)

\( \varepsilon_1, \varepsilon_2 \) = emissivity of the enclosed and enclosing surfaces respectively

\( T_1, T_2 \) = temperature of the enclosed and enclosing surfaces respectively, K

The areas \( A_1 \) and \( A_2 \) can be expressed as

\[
A_1 = \pi D_1 L
\]

\[
A_2 = \pi D_2 L
\]

where \( L \) is the length of the specimen

Since the temperature of the specimen varies along its length, an infinitesimal length \( dx \) at distance \( x \) from one end of the specimen (as shown in figure C.1) is considered and the corresponding radiation heat loss is determined by the equation below.

\[
dQ = \frac{\sigma \pi D_1 dx (T_1^4 - T_2^4)}{1 + \frac{D_1}{D_2} \left( \frac{1}{\varepsilon_1} - 1 \right)}
\]

where \( D_1 \) and \( D_2 \) are the diameter of the test specimen and inside diameter of the pyrex glass chamber.
For Bottom Specimen

From figure C.1 the temperature $T$ and length $x$ can be related by ratio and proportion. The resulting equation is given below.

$$T = 438.25 - 1899.6 \times x$$  \hspace{1cm} C.3

Plugging equation C.3 into equation C.2, integrating, and with $x = 0.025\text{m}$ the result is

$$Q_b = \frac{-\sigma \pi D_1}{1899.6 \left[ \frac{1}{\varepsilon_1} + \left( \frac{D_1}{D_2} \right) \left( \frac{1}{\varepsilon_2} - 1 \right) \right]} \left[ \frac{T^5}{5} - T^4 \right]_{T=390.76}^{T=438.25}$$  \hspace{1cm} C.4

From Holman (1986) the values of the emissivity are

$$\varepsilon_1 = 0.074 \text{ for polished stainless steel}$$
$$\varepsilon_2 = 0.95 \text{ for pyrex glass}$$

With $D_1$ and $D_2$ equal to 0.018m and 0.106m respectively the heat loss due to radiation is

$$Q_b = 0.126 \text{ W}$$

For Top Specimen

Using the same procedure used for the bottom specimen, the equation for the radiation heat loss is
Using the same values for $\varepsilon_1$, $\varepsilon_2$, $D_1$ and $D_2$ the radiation heat loss at the top specimen is

$$Q_t = 0.0279 \text{ W}$$

Adding $Q_b$ and $Q_t$, the total radiation heat loss from the two specimens is

$$Q_{\text{total}} = 0.126 + 0.0279$$
$$= 0.1539 \text{ W}$$

The total heat input is

$$Q_i = (35154.04 \text{ W/m}^2)(\pi/4)(0.018 \text{ m})^2$$
$$= 8.946 \text{ W}$$

Therefore the radiation heat loss (in percent) along the two specimens is

$$\% \text{ radiation heat loss} = \frac{0.1539}{8.946} \times 100$$
$$= 1.72\%$$
APPENDIX D
COMPUTER PROGRAM FLOW CHART FOR THE CALCULATION OF THE GAS GAP CONDUCTANCE

Start

Inputs:
1) No. of heat flux readings, n
2) Type of gas
3) Type of specimen material
4) surface roughness and slope

Initialise, $k = 0$

Read heat flux and mean junction temperature

$k = k + 1$

Calculation of the following:
- radii of curvature
- interfacial gap distortion
- Hardness
- Thermophysical properties of the specimen and the gas that are temperature dependent

Results of the above will be used for calculating:
1) thermal accommodation coefficient
2) temperature jump distance, $g$
3) mean thickness of the gas gap, $\delta$
4) Knudsen number, $N_{Kn}$

0.01 < $N_{Kn}$ < 10

Yes

$h_g = k / (\delta + g_1 + g_2)$

No

$k = n$

Yes

End

No

$N_{Kn} > 10$

Yes

$h_g = k / (g_1 + g_2)$

No

$h_g = k / \delta$