Chapter 5
Experimental Aspects

Thermal conductance of joints may be determined experimentally in several ways. However, by far the most common method uses the axial heat flow apparatus, based on the method described in ASTM E1225–09 in which the two cylinders of similar or dissimilar materials are placed end to end as illustrated in Fig. 1.2 (Chap. 1). There have been other apparatus built for specific needs, for example, to determine the contact conductance in duplex tubes when the heat flow is radial; in periodic contacts and in manufacturing processes. Also used frequently are transient heat flow measurements to establish thermal contact properties. The relative merits of steady state and transient methods are also discussed in this chapter.

In every case, before the heat transfer experiments are performed, it is necessary that profilometric measurements are made to characterise the contacting surfaces. It is also desirable to determine the microhardness or similar properties of the surfaces prior to the heat transfer tests.

Apart from heat transfer apparatus, conducting sheet and electrolytic tank analogues have been constructed and used, mainly to determine the resistance of various shapes of constrictions. Some of these equipment will also be briefly described in this chapter.

The chapter also includes a discussion of the accuracy of measurements as applicable to contact heat transfer.

5.1 Axial Heat Flow Apparatus

This apparatus is based on the method described in ASTM E1225–09 for thermal conductivity measurements using longitudinal heat flow. Several investigators have used this type of experimental rig for contact conductance measurements, for example, Cetinkale and Fishenden (1951), Williams (1966), Mikic and Rohsenow (1966), Fletcher et al. (1969) and O'Callaghan and Probert (1972).

A schematic of a typical axial heat flow apparatus is shown in Fig. 5.1. Essentially, the rig consists of two cylinders placed end to end and loaded in the axial direction either mechanically (see Fig. 5.2) or by hydraulic means. If the

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loading is achieved by other than mechanical means, then the contact load needs to be measured using a calibrated load cell. Axial heat flow is achieved by providing a heat source at the top end and a heat sink at the bottom end. Frequently, however, provision for heating as well as cooling of either end is made so that the effect of reversing the heat flow direction may be studied, without dismantling and re-assembling the specimens. Generally, the assembly is placed in a chamber that can be evacuated in order that the solid spot conductance may be isolated and determined. To transmit the mechanical load to the assembly inside the chamber, a bellows or similar device would be required. A rotary vane type vacuum pump is satisfactory for pressures down to about 10^{-3} Torr (0.133 Pa). A vacuum diffusion pump will also be needed if lower pressures of the order of 10^{-6} Torr are required. The traditional method of heating was by the use of electrical resistance coils such as Nichrome and cooling by water circulating in a coil and supplied by a constant head tank. Constant temperature circulating baths are also commonly used to provide both heating and cooling.

Heat flux meters, made of certified standard reference materials (SRM's), measure the heat flow through the specimens. They also facilitate in situ determination of the thermal conductivities of the test bars, thus eliminating the need to refer to external sources for this information.

To minimize heat losses, a guard heater or a thermal shield should be placed around the test section. This is especially important if the tests are done in a conducting medium such as air. In addition, insulators need to be placed at each end of the column assembly to prevent heat losses in the axial direction.

The usual method of measuring the temperatures along the axes of the specimens is by means of calibrated thermocouples, although other highly accurate and

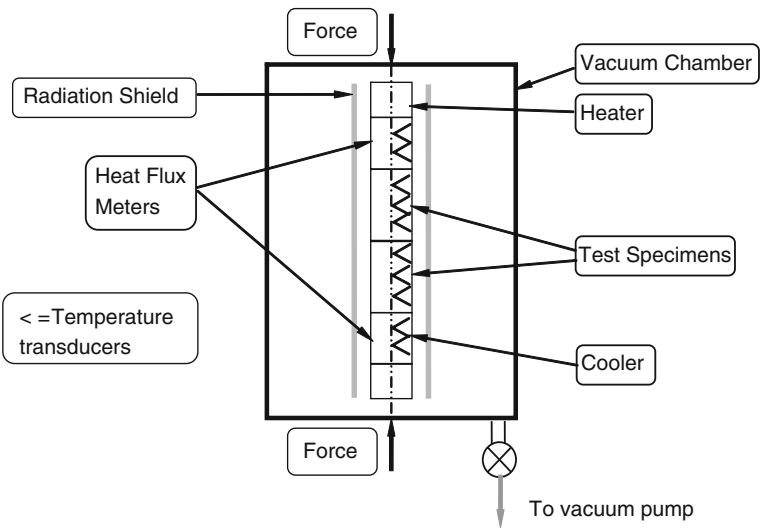

Fig. 5.1 Schematic diagram of the axial heat flow apparatus

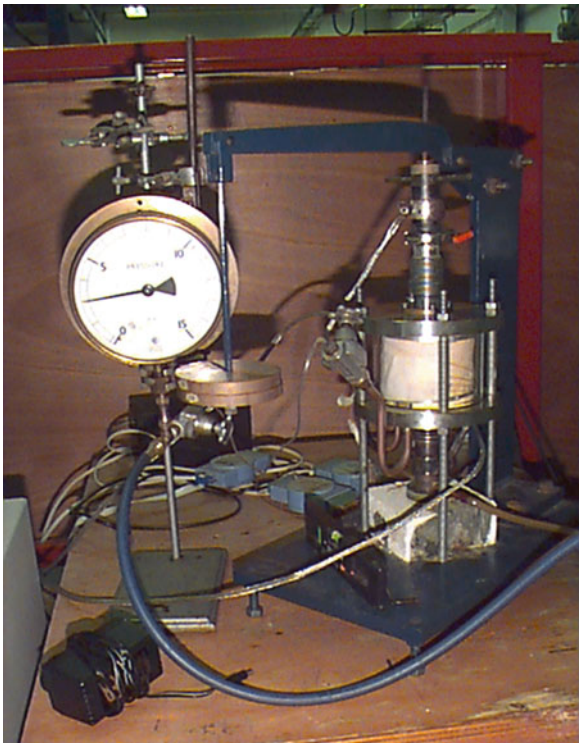

Fig. 5.2 An axial heat flow apparatus showing the mechanical loading arrangement by lever and dead-weights (Villanueva 1997)

sensitive temperature sensing devices such as thermistors and resistance temperature detectors (RTD's) are frequently used. The thermocouples are inserted in holes drilled normal to the axis and extending to the axis, that is, the length of the holes is equal to the radius of the specimen. The use of a conducting cement or a soft foil is necessary at the bottom of the hole to provide good contact between the thermocouple and the specimen. The output from the temperature sensors is usually fed into computer based data takers for immediate processing of experimental data.

Before we leave the section on axial heat flow apparatus, it is not out of place to mention one of the early experimental works (Phillips 1956) on heat transfer across joints placed in different gaseous atmospheres. A noteworthy feature of this work is to enclose just the joint in a cylindrical container or "sealing gasket", rather than place the whole assembly in a vacuum tight chamber.

The sealing gasket was machined from a solid cylinder of Teflon, four and one-half inches (114 mm) in diameter and six inches (152 mm) long. The gasket was machined 0.010 inch (2.54 mm) undersize with respect to the specimen. The gasket material was drilled and tapped to receive a 3/16 inch (4.76 mm) stainless steel nipple through which the various gaseous media were introduced. An adjustable stainless steel banding clamp was fitted over the Teflon gasket after it

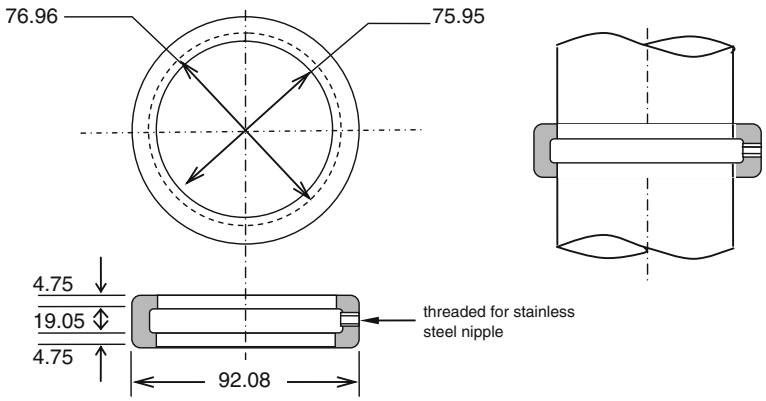

Fig. 5.3 Sealing gasket to maintain the interface in vacuum or in gaseous atmosphere

was in place on the test specimens in order to hold it more securely in place and to better enable it to hold its pressure and/or vacuum after thermal expansion. A sketch of the sealing gasket is shown in Fig. 5.3 (dimensions in mm).

Phillips was able to test the interfaces in vacuum, air and helium with the aid of this gasket alone. No vacuum (or pressure tight) chamber was needed. His results were consistent with what were reported for these conditions in later decades. If this method could be successfully applied, it would considerably simplify the design, construction and operation of axial heat flow apparatus. Of course, the lateral heat loss from the specimens should be minimised by the use of either good quality insulation (Kempers et al. 2009) or by the provision of guard heaters.

5.2 Radial Heat Flow Apparatus

In a cylindrical joint transmitting heat radially, the contact pressure is developed (or the initial shrink-fit pressure is modified) as a result of the differential expansion of the two cylinders. As will be seen in a later chapter, the differential expansion and, hence, the contact pressure are functions of the heat flux. To test these types of joints, therefore, no provision needs to be made for mechanical loading (see Cohen et al. 1960; Williams and Madhusudana 1970; Hsu and Tam 1979; Madhusudana and Litvak 1990). On the other hand it is important to be able to measure the heat flux accurately.

The essentials of a typical radial heat flow apparatus is shown in Fig. 5.4. A major problem in testing of this type of joint appears to be the difficulty in obtaining a truly axisymmetric temperature distribution in the specimens if the inside surface of the inner cylinder is heated by means of a central non-contacting rod. The use of a pre-heated liquid, instead, may alleviate the difficulty to some extent; however, this method is going to cause additional problems if testing in vacuum is required.

A second source of problems arises because of the need to make the cylinders sufficiently long to avoid the end effects; firstly, very accurate machining to close tolerances is required to ensure that the ends are straight and parallel with negligible taper; secondly, extra care is required in the assembly of long cylinders to produce a shrink fit; thirdly, it will be necessary to drill deep holes of very small diameter to locate the thermocouples inside the wall thickness of the specimens. In the apparatus shown in Fig. 5.2, temperatures were measured only on the surfaces of the specimens as it would have been impossible to locate sufficient number of thermocouples along the radial co-ordinate to measure the temperature distribution reliably. Perhaps because of these difficulties, there has been comparatively small number of reports dealing with the experimental investigation of radial heat flow in composite cylinders.

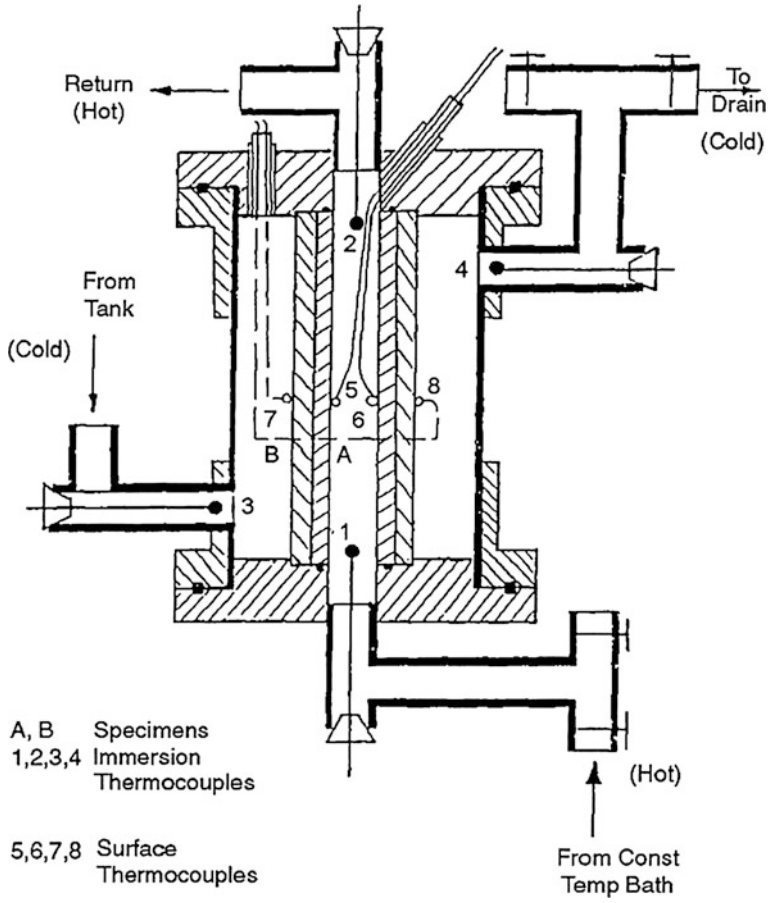

Fig. 5.4 Radial heat flow apparatus (Madhusudana and Litvak 1990)

An associated problem is the determination of TCR in finned tubes. Experimental apparatus specially devised for this application (Cheng and Madhusudana 2006) is described in a later chapter.

5.3 Periodic Contacts

There are several applications in which the heat transfer occurs between surfaces that are undergoing a regular cycle of contact and separation. Examples include the heat transfer between the exhaust valve and its seat in an internal combustion engine, the heat transfer between the die and the work piece in a repetitive hot metal deformation process.

Some experimental apparatus used to test periodic contacts is similar to the axial heat flow facility described earlier. The experimental apparatus designed by Dodd and Moses (1988) is shown in Fig. 5.5. The arrangement used to make and break the contact in one such apparatus is as follows.

The contact mechanism consists of two parts, one located directly above the other. The upper plate, made of nylon, is rigidly attached to the support frame. Suspended below the plate, by means of a spring-loaded mechanism is a smaller nylon plate to which one of the thermal reservoirs is attached. A nylon alignment ball is sandwiched between the plates. In conjunction with the spring-loaded mechanism, the ball requires the contact force to be transmitted through a single point, thus allowing the entire reservoir assembly and the attached specimen to

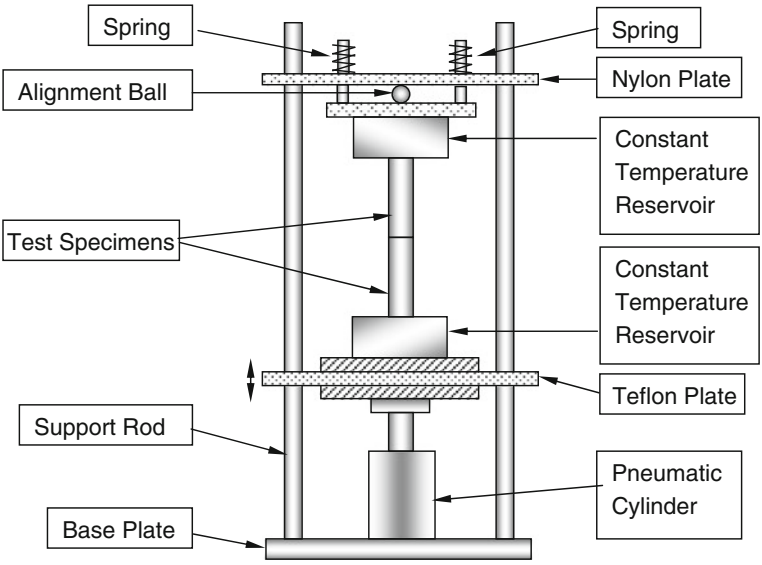

Fig. 5.5 Experimental apparatus for periodic contacts (after Dodd and Moses 1988)

pivot about that point, bringing the surfaces of the specimens into contact in their entirety. The second test specimen and its associated thermal reservoir is attached to the lower plate, made of Teflon, which is free to slide along the four PVC rods forming the support frame.

The test specimens were caused to contact and separate by driving the lower plate by means of a pneumatic cylinder. The airflow to the cylinder was controlled by a dual acting solenoid valve, with one air stream used to drive the test specimen into contact and the other to separate the two at the end of the contact period of the cycle. The valve was micro-processor controlled and the data was processed by the use of a Data Acquisition and Control unit.

In an earlier investigation by Howard (1976) into periodic contacts, it was the upper bar that was moved by actuating the pneumatic cylinder. Both apparatus allowed tests to be conducted in ambient atmosphere only—there was no provision for evacuating the test section.

5.4 Transient Measurements

The advantages claimed for the steady state method are simplicity, direct measurements without having to rely on "handbook" data for properties such as the thermal conductivities of test materials, accuracy and simple calculations required to estimate the conductance. The main disadvantage of steady-state methods is the long time it takes to perform each set of experiments. On the other hand, results are obtained relatively quickly in transient measurements. In general, the thermal contact resistance is determined by matching the measured temperature–time history with the numerically predicted one by means of fitting parameters. However, these techniques invariably require independent measurements of such thermophysical properties as the specific heat or the thermal conductivity of the sample materials. Further, the conductance values determined are time-dependent and corrections need to be applied to them before they are used in thermal design of apparatus. These factors introduce additional uncertainties.

Transient numerical methods are necessarily implicit. The measured variation of the temperature with time in one or both of the specimens in contact is compared against that obtained from a numerical (or analytical) approach with an assumed value of the thermal resistance. The thermal resistance in the numerical model is then adjusted until the computed values agree with the measured values.

5.4.1 Transient Methods

In some experimental methods using the transient approach, the two surfaces are initially in contact at the same temperature. At the start of the experiment, a temperature disturbance is introduced by heating and/or cooling one of the

specimens. Bosch and Lasance (2000), for example, describe a facility in which a sample is sandwiched between a copper upper cylinder and an aluminium support. There are thus two interfaces: copper/sample and sample/aluminium (Fig. 5.6). The aluminium support can be heated or, alternatively, maintained at ambient temperature by connecting it to one of two water baths. The assembly is initially in thermal equilibrium at ambient temperature. The hot water is switched on for about 30 s followed by a switch back to ambient temperature. The temperature–time histories of the copper block and the aluminium support are recorded. These are then compared with the results of a *numerical simulation* using the total resistance, R_{th} defined below, as the fitting parameter.

$$R_{th} = d/(kA) + 2R_c$$

In this expression:

k = thermal conductivity of the sample
A = area of sample normal to heat flow
d = thickness of the sample
R_c = thermal contact resistance of either interface

Literature values of the thermal conductivity were used in evaluating the above equation.

In the *laser-flash method* for measuring the thermal diffusivity of a material, a small disc-shaped sample (about the size of a small coin) is subjected to a very short burst of radiant energy in the form of the laser-flash. The duration of the irradiation time is one millisecond or less. The resulting temperature rise of the rear surface of the sample is measured and thermal diffusivity values are computed from the temperature rise versus time data (Fig. 5.7).

The theory behind the method is as follows (Hohenauer 1999):

For one dimensional flow of heat

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\left(\frac{\partial T}{\partial t}\right) \tag{5.1}$$

Solving by separation of variables

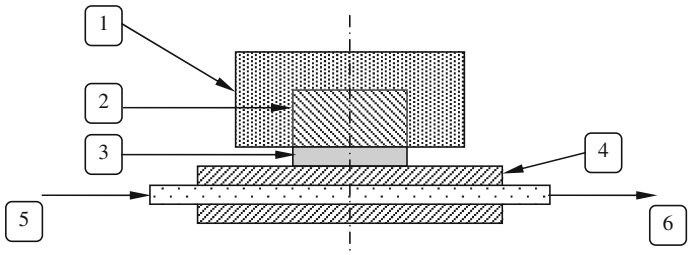

Fig. 5.6 Transient heat flow apparatus. *1* Insulation *2* Copper block *3* Specimen *4* Aluminium block *5* Water inlet *6* Water outlet

$$T(x,t) = \left[A\sin\sqrt{\frac{c}{\alpha}}x + B\cos\sqrt{\frac{c}{\alpha}}x\right]e^{-ct} \tag{5.2}$$

For no heat loss from the surface at $x = 0$, we must have $A = 0$. The second boundary condition, $\frac{\partial T}{\partial x} = 0$ at x = d (where d is the thickness of the sample) gives

$$c = \frac{n^2\pi^2\alpha}{d^2}$$

Therefore, the solution will be of the form

$$T(x,t) = \sum_{n=0}^{\infty}\left[B_n cos\frac{n\pi x}{d}\right]e^{-\frac{n^2\pi^2\alpha t}{d^2}} \tag{5.3}$$

For t = 0, this equation may be rewritten as

$$T(x,0) = B_0 + \sum_{n=1}^{\infty}\left[B_n cos\frac{n\pi x}{d}\right] \tag{5.3a}$$

The heat pulse, applied when t = 0, is of infinitesimal duration, With this condition, B_0 and B_n may be evaluated as: $B_0 = T_0 + \Delta T_{max}$ and $B_n = 2\Delta T_{max}$ where T_0 is the initial temperature and T_{max} is the temperature reached by the entire specimen after a sufficiently long temperature; $\Delta T_{max} = T_{max} - T_0$. Hence

$$T(x,t) = T_0 + \Delta T_{max}\left[1 + 2.\sum_{n=1}^{\infty} cos\frac{n\pi x}{d}e^{-\frac{n^2\pi^2\alpha t}{d^2}}\right] \tag{5.4}$$

and

$$T(d,t) = T_0 + T_{max}\left[1 + 2.\sum_{n=1}^{\infty}(-1)^n e^{-\frac{n^2\pi^2\alpha t}{d^2}}\right] \tag{5.4a}$$

Using the *first order approximation*, the half-time, that is, the time required for the rise of temperature to reach *half* its maximum value, is then given by

$$\frac{\Delta T}{\Delta T_{max}} = \frac{1}{2} = \left[1 + 2(-1)e^{-\frac{n^2\pi^2\alpha t}{d^2}}\right] \tag{5.5}$$

This gives

$$\frac{1}{4} = \left[e^{-\frac{\pi^2\alpha t_{0.5}}{d^2}}\right] \tag{5.6}$$

Taking logarithms and solving for α,

$$\alpha = -\frac{ln\left(\frac{1}{4}\right)}{\pi^2}\left(\frac{d^2}{t_{0.5}}\right) = 0.140\left(\frac{d^2}{t_{0.5}}\right) \tag{5.7}$$

Thus, the diffusivity can be determined once the half-time, $t_{0.5}$, is estimated from the graph (Fig. 5.7).

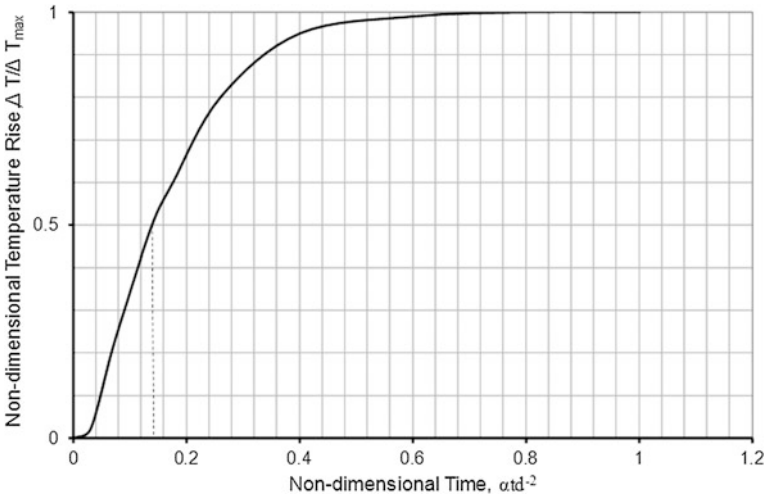

Fig. 5.7 Transient temperature–time graph showing half-time

Note The above analysis is based on simplifying assumptions. Recent software for the analysis of results from the laser flash apparatus allows for non-adiabatic boundary conditions and energy pulses of finite duration.

When the laser-flash apparatus is used to determine thermal contact conductance, a fitting procedure is normally used. A series of temperature–time graphs are first obtained (by numerical analysis) for the sample with an interface, for various assumed values of TCC. The TCC corresponding to that graph which matches experimentally measured temperature–time graph is taken to be the TCC of the sample.

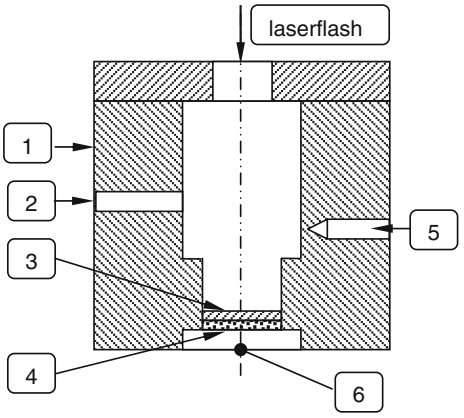

Fig. 5.8 Part of a laser flash apparatus. *1* Pressure chamber. *2* Gas inlet/outlet. *3* Copper plate. *4* Specimen. *5* Thermocouple well. *6* MgF_2 window

Griesinger et al. (1998) used the laser-flash apparatus for the measurement of the TCC between a solid (copper) surface and zeolite powder (Fig. 5.8). In this case, the duration of the pulse is of the order of 1 s or less. *Again, the TCC is determined by an inverse procedure*. The numerically calculated temperature rise at the back of the specimen (zeolite layer) is matched with the measured temperature rise using (assumed values of) the TCC, as well as the thermal diffusivities of copper and zeolite as the fitting parameters. The tests could be conducted in chamber pressures from 0.0015 bar (150 Pa) to 1 bar (100 kPa).

Although accuracies of 1 % are claimed for the diffusivity of single material samples, the uncertainties associated with laser-flash measurements of TCC are not yet established. Greisinger et al. claim that the results are reproducible to +10 %.

The experimental approach presented by Fieberg and Kneer (2008) was based on transient infrared temperature measurements. Two bodies initially at two different temperatures were brought in contact and the surface temperature histories were recorded with a high-speed infrared camera. The contact heat flux was calculated by solving the related inverse problem. From the contact heat flux and from the measured temperature jump at the interface the contact heat transfer coefficient was calculated.

The inverse method used for the calculation of the heat flux was based on the analytical solution for a semi-infinite body and a step response to a Neumann (heat flux) boundary condition.

Readers interested in theoretical analysis may like to refer to the analytical solution for determining the TCR between the materials of a double layer sample using laser flash method presented by Milosevic et al. (2002).

As the name implies, the transient contact conductance is a function of time. It is, therefore, sometimes claimed that the use of steady state conductance values for transient conditions will result in a large error. It is interesting, therefore, to consider how the TCC varies with time.

An original work analyzing the variation of the *constriction resistance* with respect to time is that of Schneider et al. (1977). As we have seen earlier, the constriction resistance is the resistance associated with a *single* contact spot of radius a and TCC is the sum of the reciprocals of all of the constriction resistances in the contact plane. The results of their numerical analyses for copper/stainless steel, copper/glass, copper/steel and steel/glass interfaces could be correlated into a single equation:

$$\frac{R_{tr}}{R_{ss}} = 0.43\tanh[0.37ln(4X)] + 0.57 \tag{5.8}$$

where

R_{ss} = steady state constriction resistance

R_{tr} = transient constriction resistance

X = correlation parameter $= 0.5\left[1 + \sqrt{\alpha_2/\alpha_1}\right]F_{o,\alpha}$

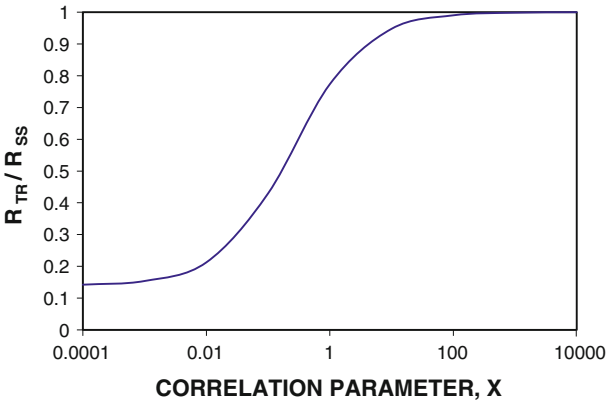

Fig. 5.9 Variation of disc constriction resistance with time [Plotted from Eq. (5.8), Schneider et al. 1977]

Table 5.1 Time required for the constriction resistance to reach the steady state value

Material 1/material 2	α_1 (m^2/s) $\times 10^5$	α_2 (m^2/s) $\times 10^5$	$F_{o\alpha}$ for steady state	Time for steady state, seconds
Copper/steel	13.2	1.36	151.40	0.0055
Steel/glass	1.36	0.06	165.28	0.1294
Copper/stainless steel	13.2	0.49	167.69	0.0160
Copper/glass	13.2	0.06	187.37	0.1412

$\alpha_m = 2\alpha_1\alpha_2/(\alpha_1 + \alpha_2)$.
$F_{o,\alpha} = \alpha_m t/a^2$.
α = thermal diffusivity, ρ/kC
ρ = density
C = specific heat
The results are shown plotted in Fig. 5.9
With X as defined above, we see that the Fourier Number is

$$F_{o,a} = \frac{2X}{1 + \sqrt{\alpha_2/\alpha_1}}$$

Therefore, for a given pair of surfaces $F_{o,a}$ is directly proportional to X. Consequently X is a measure of the time elapsed. From Fig. 5.7, we see that the full, or steady state, value of the constriction is reached when $X \approx 100$. The average contact spot radius is 30 μm. The Table 5.1 may, therefore, be constructed.

Since the time taken to reach the steady state value is only a fraction of a second, it is unlikely that an error is introduced on this basis. This discussion applies only to the constriction resistance. In the actual experiment, of course, allowance must be made for the thermal capacities of the solid blocks and the

specimen. It is equally important, of course, that the time constants for the measurement system, including the temperature sensors, be as small as practicable in order that the temperature–time history is faithfully recorded. Alternatively, appropriate corrections must be applied to the measurements.

5.4.2 Transient Measurements: Conclusions

As a result of the above discussion of transient measurement techniques, and the comparison with the steady state procedures, we can list the following conclusions:

- Steady-state method allows direct measurements to be made without the need for further measurements in separate apparatus to determine other required thermal properties.
- The transient methods are implicit and, in general, depend on matching the results of numerical analysis with the measurements by means of fitting parameters. (Note that built-in sophisticated software is available with modern laser flash apparatus, eliminating the need for separate analysis).
- These methods also depend on separate thermal property measurements or, alternatively, data from literature, for final results. For these reasons, there is inherently more uncertainty in the results of transient measurements.
- While the constriction resistance itself reaches the steady-state value very quickly, in the actual experiment allowance must be made for the thermal capacities of the solids on either side of the sample and the sample material itself. Thus, care must be taken to see that steady-state values are not used for transient conditions.
- For transient measurements, the time constants for the measuring system need to be as small as practicable. Corrections should be applied if necessary.
- The main disadvantage of the steady-state measurements is the relatively large time taken for each set of data to be reproduced. For this reason, transient methods may be used if the time available is short.

Transient methods, of course, are also necessary when the contact process itself is transient, e.g., intermittent contacts, manufacturing processes and dry friction. A comparison of steady state and transient techniques was presented by Madhusudana and Garimella (2003).

5.5 Analogue Methods

With the wide availability of dedicated software and consequent ease to model systems of complex geometry, the analogue methods, in general, have gone out of favour in the solution of heat transfer problems. Nevertheless, the a brief discussion is included

a. to provide a historical perspective to contact heat transfer research

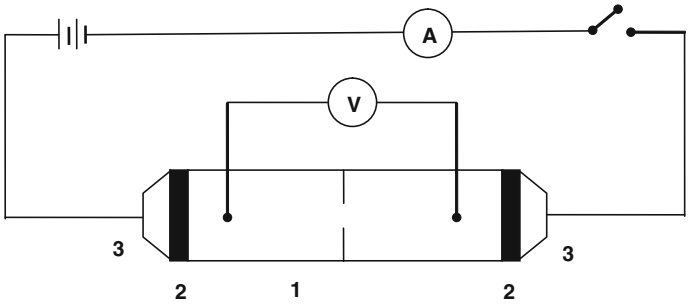

Fig. 5.10 Conducting sheet analogue for two-dimensional constrictions. *1* Conducting sheet. *2* Silver paint. *3* Clips

b. so that the similarity between heat transfer and other physical phenomena may be appreciated.

The analogue method is often a quick and inexpensive way of obtaining solutions to potential flow problems. In the current context, this method depends on the similarity between the electric voltage and the temperature since both these potentials obey the same (Laplace) equation. In contact resistance work, the analogue approach is used mainly to determine constriction resistances of various types.

For two-dimensional problems in the x−y plane, the problem is easily simulated. The heat flow region is simulated by an electrically conducting sheet ("teledeltos" paper). Prescribed voltages are applied to the silver painted ends of the paper to simulate isothermal boundary conditions (see, for example, Veziroglu and Chandra 1969). The schematic of the set-up is shown in Fig. 5.10. A cut is made in the middle of sheet to avoid any electrical contact across the cut.

The resistance with and without the cut is measured, from which the additional resistance due to constriction is calculated by the difference. Note that, in this method, it is also easy to obtain the equipotential lines (isotherms) by the use of standard equipment such as Servomex Field Plotter. The analogy has also been used in the determination of fin conduction shape factors required in the analysis of finned-tube heat exchangers (Sheffield et al. 1987).

For three-dimensional problems, it is necessary to use an electrolytic tank analogue (Karplus 1958). This type of equipment has been used to measure the resistance of:

1. Single constrictions of various shapes (Major and Williams 1977; Madhusudana 1992)
2. Single and multiple constrictions of circular shape (Jeng 1967; Yip and Venart 1968; Cooper 1969)
3. Macroscopic resistance in a bolted joint (Fletcher et al. 1989).

A diagram of the electrolytic cell used to determine the resistance of a single constriction is shown in Fig. 5.11. The following points must be noted in the design and use of an electrolytic tank analogue:

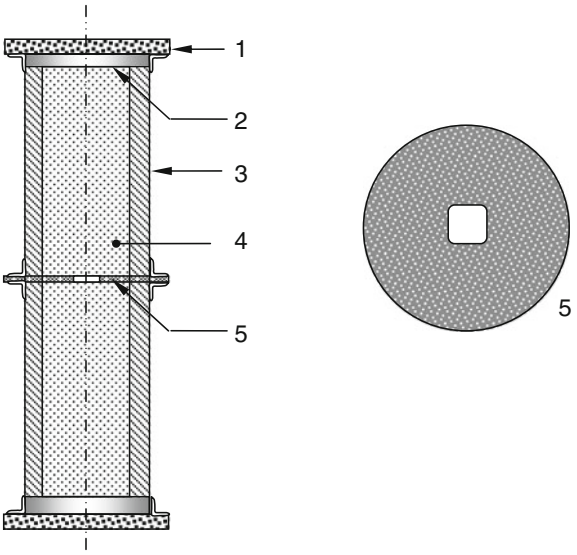

Fig. 5.11 Electrolytic tank analogue for three dimensional constrictions. *1* Perspex plate. *2* Brass electrode (Graphited). *3* PVC Pipe. *4* Electrolyte. *5* Constriction sheet

1. A container is fabricated in such a way that the shape of the electrolyte within the container is a scale model of the field configuration. Boundaries, which are equipotential, are made of metal while insulating materials or employed for adiabatic boundaries.
2. To avoid polarisation, AC voltages (frequency range 50–1,500 Hz) should be used.
3. The electrolyte must be purely resistive.
4. To minimise errors, the resistivity of the electrodes must be small compared to the resistivity of the electrolyte.
5. The surface impedance of the electrodes must be minimised by the use of graphite or platinum black coatings.

If the measurement of the resistance is the only requirement, then the method is quite simple. The constriction is simulated by a plastic sheet cut to the required shape. Two measurements of the conductivity of the cell is made—one with the constriction in place and the other without the constriction—by means of an AC conductivity meter. Alternatively, the resistance may be measured in a universal bridge. Knowing the dimensions of the tank, the additional resistance due to constriction may be calculated.

If the temperature profile is also required, then a device such as the electronic-analogue field mapper, as described by Karplus (1958), may be used. However, since we are mainly interested in determining the resistances, the additional complexities involved will defeat the purpose of obtaining quick and simple solutions. Furthermore, if an accurate temperature is required, then it is desirable to perform a numerical analysis.

5.6 Accuracy

Contact heat transfer measurements, in general, are subject to error because of various uncertainties, including those in thermocouple calibration and location, and in thermal conductivity values required to calculate the heat flux. The experimental values are also affected by the heat transfer between the specimens and the surroundings.

Madhusudana (2000) presented a detailed analysis of possible heat losses in an axial flow apparatus for the measurement of TCC. The major conclusions were:

1. The heat loss from the specimen to the surroundings represents a major source of uncertainty in contact heat transfer experiments especially when:
   - the contact pressures are low
   - the specimens are poor conductors
   - there is significant flatness deviation in the surfaces of contact
2. At high temperatures (>450 K), radiation heat loss becomes significant.
3. All of the heat losses, especially that due to radiation, may be considerably reduced by the provision of a radiation shield.
4. Unless the contact pressure is very low or the flatness deviation is large, moderate vacuums of the order of 10^{-2} Torr (1.33 Pa) are satisfactory when we consider other sources of inaccuracy such as that in temperature measurement.

In an axial heat flow apparatus, with careful design and experimentation, an experimental uncertainty of <10 % is achievable for tests conducted in vacuum. For tests conducted in a conducting medium such as air, an uncertainty of 15 % is probably more representative of the accuracy to be expected. The uncertainty, especially in a conducting environment, can be reduced by the provision of carefully controlled guard heaters.

In radial heat flow apparatus, because of the difficulties in obtaining truly axisymmetric heat distribution, in locating thermocouples accurately, and because of end effects, it is unrealistic to expect an accuracy of better than 20 % when tests are done in a conducting medium. A higher accuracy could be obtained for tests in vacuum.

Transient methods, in general, depend on separate thermal property measurements or, alternatively, data from literature, for final results. For transient measurements, the time constants for the measuring system need to be as small as practicable The transient methods are implicit and, in general, depend on matching the results of numerical analysis with the measurements by means of fitting parameters. All of these factors contribute toward uncertainties in the results of transient measurements. According to the authors quoted earlier in this chapter, accuracies of the order of 10 % are still achievable with transient techniques. With analogue methods, the uncertainty is controlled mainly by the accuracy of manufacture of the apparatus and the specimens, and the voltage measurement. With careful experimentation, uncertainties of <5 % may be reasonably accepted in both the conducting sheet and the electrolytic tank analogues. The analogue

methods, however, have been mainly useful in the analysis of constriction resistance.

It is worth noting that, the very nature of contact resistance, depending as it does on the surface topography, and material properties, introduces an uncertainty that requires tests to be performed on several pairs of similarly prepared specimens to obtain reliable estimates. No such requirement is necessary for surfaces that are isotropic and random (e.g., lapped and bead blasted flat surfaces). Finally, it should be pointed out that the theoretically predicted values are also subject to error due to their dependency on measured values of (variable) microhardness and the surface profiles.

5.7 Summary

The foregoing is just a brief description of the main features of the more common types of equipment used in the experimental determination of TCR in different situations. Space does not permit a more exhaustive discussion of design considerations and details of instrumentation. Because of the rapid progress in technology and, in particular, microprocessor-based measurement and control, it is felt any such detail would have limited value. Readers interested in more information, however, may consult the references listed at the end of this chapter.

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