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Chapter 5

Thermal Conductivity of Liquid Metals

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Additional information is available at the end of the chapter

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Abstract

Over the last decades, many experimental methods have been developed and improved to measure thermophysical properties of matter. This chapter gives an overview over the most common techniques to obtain thermal conductivity λ as a function of temperature T. These methods can be divided into steady state and transient methods. At the Institute of Experimental Physics at Graz University of Technology, an ohmic pulse-heating apparatus was installed in the 1980s, and has been further improved over the years, which allows the investigation of thermal conductivity and thermal diffusivity for the end of the solid phase and especially for the liquid phase of metals and alloys. This apparatus will be described in more detail. To determine thermal conductivity and thermal diffusivity with the ohmic pulse-heating method, the Wiedemann-Franz law is used. There are electronic as well as lattice contributions to thermal conductivity. As the materials examined at Graz University of Technology, are mostly in the liquid phase, the lattice contribution to thermal conductivity is negligibly small in most cases. Uncertainties for thermal conductivity for aluminum have been estimated ±6% in the solid phase and ±5% in the liquid phase.

Keywords: thermal conductivity, ohmic pulse-heating, Wiedemann-Franz law, sub-second physics, high temperature, liquid phase

1. Introduction

Knowing thermophysical properties, i.e., properties that are influenced by temperature, of metals and alloys is not only of academic interest, but also profoundly important for industry and commerce. Casting of metal objects, made of, e.g., steel or aluminum, is prone to casting defects and imperfections. Therefore, in the majority of modern production procedures, computer simulations are performed to reduce defects and imperfections as well as generally

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optimize manufacturing processes. The driven benefits from such simulations often are limited by an insufficient or lacking access to experimentally obtained data. It is especially the liquid phase of metals and alloys, that is of interest, as such production processes like, e.g., casting, naturally take place in the liquid phase.

The term thermophysical properties include various properties: thermal conductivity, thermal diffusivity, thermal volume expansion, heat capacity, density, viscosity and so on. Many of those properties are important in industrial processes; however, it is thermal conductivity, more precisely, thermal conductivity of liquid metals and alloys that will be discussed in this chapter.

Naturally, the numbers of experimental methods to measure the desired quantities that have been developed over the past decades are manifold. It is the goal of this work to give a brief overview of the most common or practical techniques in Section 2, but only few of these methods are suitable to conduct measurements in the liquid phase. These techniques will be highlighted in Section 2.

At the Thermo- and Metalphysics group at Graz University of Technology, fast pulse-heating experiments are performed to measure thermophysical properties of liquid metals and alloys. The Wiedemann-Franz law is applied to calculate thermal diffusivity and thermal conductivity from measured quantities. These mentioned calculations are briefly explained in Section 3, and the experimental apparatus used is described in Section 4.

2. An overview of methods to measure thermal conductivity of liquid metals

In principle, there are three different classes of measurement methods:

- Steady state methods
- Non-steady state methods
- Transient methods

However, it is not always as easy to classify a certain technique. Especially, distinguishing between non-steady state methods and transient methods can be challenging.

Steady state methods are defined as techniques, where the temperature gradient remains constant across the sample. Those methods require precise temperature control throughout the whole experiment to confine convection effects to a minimum, which is especially hard to achieve for metals with high melting points.

Transient methods and non-steady state methods make use of very short time frames in order to conclude measurements before convection plays a role. Non-steady state methods achieve those conditions due to very high heating rates of up to 1000 Ks^{-1}, with rather large temperature gradients of over 100 K.

The temperature gradient in transient methods is significantly lower (on the order of 5 K) than in non-steady state methods, which minimizes the possibility of convection-induced effects in the measurements. In recent history transient methods grew in importance and started to replace non-steady state methods.

2.1. Steady state methods

2.1.1. Axial heat flow method

A known heat flux q is applied to one end of a sample and dissipated on the other end by a heat sink. Thermal conductivity can be calculated by

$$\lambda = \frac{q}{A} \cdot \frac{\Delta z}{\Delta T} \tag{1}$$

where q is the applied heat flux, A is the specimen cross-section, and $\frac{\Delta z}{\Delta T}$ is the inverse temperature gradient across two points z_q and z_2.

Therefore, the conditions to determine thermal conductivity with this method is the determination of the geometry A and Δz, guarantee that the heat flow is unidirectional, measurement of the heat flux q, and measurement of temperature of at least two points z_q and z_2 (normally thermocouples).

While this technique is mostly targeted at solid materials, it can be used on a variety of liquid metals with low melting points such as mercury, lead, indium, and gallium [1].

The temperature range is 90–1300 K, and the accuracy in this range has been estimated to be ±0.5 to ±2% [2].

2.1.2. Radial heat flow method

Another method to measure thermal conductivity for both solid and liquid materials is the concentric cylinder method.

The solid sample is placed in-between two concentric cylinders, and a known heat flux is applied by leading a heater through the inner cylinder. The outer cylinder is water cooled to provide a temperature gradient between the two cylinders.

The temperature difference between temperature sensors (often thermocouples) in the two cylinders is determined when steady state is achieved. Knowing the radii of the two cylinders and their length, thermal conductivity can be calculated by

$$\lambda = \frac{q}{L} \cdot \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 \cdot \pi \cdot \left(\mathrm{T}_1 - \mathrm{T}_2\right)} \tag{2}$$

with q being the applied heat flux, L as the length of the cylinders, r_1 as radius of the inner cylinder, r_2 as radius of the outer cylinder, and T_1 and T_2 as the respective temperatures.

A more in-depth explanation of this method can be found in [2].

The method can be adapted for liquid metals by providing a container for the liquid sample in-between the two concentric cylinders. Apart from this container, the measuring principle remains the same for liquid metal samples.

The radial heat flow method operates in a temperature range of 4–1000 K and the uncertainty of this method has been estimated to be about ±2% [3].

2.2. Direct heating methods

The term "direct electrical heating method" summarizes all those measurement techniques, where the sample is heated up, by running a current through it, without an additional furnace. An example of such a method, but in a dynamic way and not as a steady state method, is the ohmic pulse-heating method that will be discussed later in this chapter.

Direct electrical heating methods are therefore limited to samples which are decent electrical conductors. The shape of the samples can vary from wires, rods, sheets to tubes. The advantage of such techniques is for one, the lack of a furnace and, secondly, the possibility to measure a multitude of thermophysical properties simultaneously.

Direct heating methods are able to achieve high temperatures of about 4000 K and are therefore suitable for measuring thermal conductivity in the liquid phase of metals with high melting points.

2.2.1. Guarded hot plate

This steady state method utilizes two temperature-controlled plates that sandwich a solid disc-shaped sample. Heating one plate, while cooling the other one, generates a uniformly distributed heat flux through the sample, achieving a steady state temperature at each plate. The technique is considered as the steady state method with the highest accuracy.

The guarded hot plate apparatus can be constructed in single sided or double sided mode. When operated in double sided mode, there is a total amount of three plates as well as two samples: A central heater plate together with two cooling plates sandwiching the two samples. The temperature drop across the two specimens is measured with thermocouples, which are apart a distance L. Thermal conductivity can then be determined by

$$\lambda = \frac{q \cdot L}{2 \cdot A \cdot \Delta T} \tag{3}$$

where q is the heat flux through the specimen, A is the cross section, L is the spatial distance between the two thermocouples, and ΔT is the temperature difference.

In the single-sided mode, one of the cooling plates as well as the second specimen is removed. The temperature gradient in one direction therefore vanishes, which leads to the loss of a factor 2 in Eq. (3)

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$$\lambda = \frac{q \cdot L}{A \cdot \Delta T} \tag{4}$$

The experimental setup and the calculation of the thermal conductivity are more thoroughly explained in [4].

Commercially available guarded hot plate (GHP) apparatus, like the NETZSCH GHP 456 Titan [5], operate in a temperature range of 110–520 K and provide an accuracy of ±2%.

It has to be noted that the GHP method is applicable only for solid samples and it is not a suitable method to determine thermal conductivity of high-melting metals.

2.2.2. Calorimeter method

The calorimeter technique is a direct measurement of Fourier's law. It consists of a heating source (typically SiC or $MoSi_2$ elements) and a SiC slab to distribute the temperature gradient. The specimen is enclosed by two insulating guard bricks, which are, like the specimen as well, in thermal contact with a water-cooled copper base. As the name gives away, the central part of the system is a calorimeter, which is surrounded by the guards. The apparatus is designed in a way that the heat flow into the calorimeter is one-dimensional.

Two thermocouples, which are apart a distance L and lie vertically to each other, are enclosed in the specimen and the temperature difference $T_2 - T_1$ between them is measured.

Thermal conductivity can be determined by

$$\lambda = \frac{\frac{dq}{dt} \cdot L}{A(T_2 - T_1)} \tag{5}$$

with A being the cross section of the calorimeter, L as the distance between the two thermocouples, $\frac{dq}{dt}$ as the rate of heat flow into the calorimeter, and $T_2 - T_1$ as the temperature difference between the two thermocouples.

2.3. Transient methods

2.3.1. Transient hot wire and transient hot strip method

Simple experimental arrangements and short measurement times are granted by the transient hot wire (THW) along with the transient hot strip (THS) method.

The transient hot wire technique is most commonly used for measuring thermal conductivity λ and thermal diffusivity a. An electrically heated wire, which acts as a self-heated thermometer is placed into a material and distributes a radial heat flow into the sample. The specimen itself acts as a heat sink for the system, while the wire functions as a heat source as well as providing a mechanism to measure the thermal transport properties, due to a temperature-dependent drop of the voltage along the wire. Solving the fundamental heat conduction equation yields

$$\Delta T(r, t) = \frac{q}{4 \cdot \pi \cdot \lambda} \cdot \ln\left(\frac{4 \cdot a \cdot t}{r^2 \cdot e^{\gamma}}\right), \tag{6}$$

with q the heat input per unit length of the wire, r the radius of the wire, a the thermal diffusivity, γ Euler's constant, t the time, and λ, of course, the thermal conductivity.

An in-depth explanation of this method to determine thermal conductivity is given in [6, 7].

The transient hot strip (THS) method further improves the THW method. Instead of a wire as the heat source and measuring device, a thin strip of metal foil is used. The metal foil provides a greater surface as well as a smaller thickness than the heated wire, leading to a lower density of heat flow and consequently, a smaller thermal contact resistance to the sample.

While the THW method is only applicable for liquids and some solids, which can be wrapped around the heating wire in a way the thermal resistance is low enough, the THS method is the go-to method to perform measurements on solids.

Note: this work focuses on the measurement techniques for thermal conductivity of liquids. THS measurements are also performed on gases (see [8]).

At Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, an upgraded version of the THS and THW method, the transient hot bridge technique, has been developed. In this method, a total of eight strips are deployed in a way they form a Wheatstone bridge, allowing an effective thermal and electrical self-compensation [9].

Uncertainties of the THW technique have been reported (e.g., see [10]) to be ±5.8% for the determination of thermal conductivity. However, the method has also be described as even more accurate [11], with uncertainties of below ±1% for gases, liquids, and solids. With a maximum temperature of about 1000 K, this method is only suitable for low melting metals.

2.3.2. 3ω method

The 3ω method goes back to the work done by Cahill [12] in 1987. The method has similarities with the THS and THW technique, since it also uses a single element as heat source as well as thermometer. While both the THS and THW method measure temperature in dependence of time, the 3ω technique records the amplitude and phase of the resistance depending on the frequency of the excitation.

It is most commonly used as a technique to measure thermal conductivity of solids or liquids, but has been improved to also be applicable on thin films [12, 13]. A conducting wire is distributed onto a specimen and an AC voltage with a frequency ω is driven through it. Due to the electrical resistance, the sample is heated up, resulting in a temperature change. The frequency of the change in temperature is 2ω. The product of the resistance oscillation 2ω and the excitation frequency ω gives a voltage of frequency 3ω, which is measured and responsible for the name 3ω method.

Measuring the 3ω voltage at two frequencies f_1 and f_2, thermal conductivity is

$$\lambda = \frac{V^3 \ln f_2/f_1}{4 \cdot \pi \cdot l \cdot R^2 \left(V_{3,1} - V_{3,2}\right)} \frac{\mathrm{d}R}{\mathrm{d}T} \tag{7}$$

with $V_{3,1}$ the 3ω voltage at frequency f_1, $V_{3,2}$ the 3ω voltage at frequency f_2, and R the average resistance of the metal line of length l.

In the original work of Cahill [13], the temperature range of the 3ω method is 30–750 K, which is not suitable for high melting metals. This method often is applied on nanofluids and publications state an uncertainty of around ±2% [14].

2.3.3. Laser flash method

Under the laser flash method (LFM), the directly measured quantity is thermal diffusivity and not thermal conductivity. Thermal conductivity can, however, be determined with knowledge of specific heat as well as density of the sample.

$$\lambda(T) = a(T) \cdot \rho(T) \cdot c_p(T), \tag{8}$$

with $a(T)$ the thermal diffusivity, $\rho(T)$ the density, and $c_p(T)$ the specific heat.

In the LFM, the sample is exposed to a high intensity laser pulse at one face, which generates heat at said surface. On the back surface, which is not exposed to the laser pulse, an infrared sensor detects a rising temperature signal, due to heat transfer through the sample.

For adiabatic conditions, thermal diffusivity can be obtained by

$$a = 0.1388 \frac{l^2}{t_{0.5}}, \tag{9}$$

with l the sample thickness and $t_{0.5}$ the time at 50% of the temperature increase.

LFM, as introduced by Parker et al. [15], has been a convenient technique to determine thermal diffusivity a and thermal conductivity λ of solids at moderate temperatures. The method has been further improved since then and is applicable for a great temperature range, up to around 2500°C.

In 1972, Schriempf [16] applied LFM to determine thermal diffusivity for liquid metals at high temperatures. The liquid metal has to be placed in a suitable container in order to arrange a proper setup. Problems arise for liquids of low thermal conductivity. When the thermal conductivity of the sample is of the same order as of the container, this leads to an unneglectable heat current through the container. Therefore, it was proposed in [17] not to insert the liquid sample into a container, but have it placed between a metal disc, which is exposed to the laser pulse.

Commercially available laser flash apparatus like the NETZSCH LFA 427 [18] operate in a temperature range from −120 to 2800°C, depending on the furnace and are therefore applicable for higher melting metals as well.

Kaschnitz [19] estimates uncertainties of thermal conductivity for LFM to be between ±3 and ±5% in the solid phase and ±8 to ±15% in the liquid phase.

Hay [20] did an uncertainty assessment for their apparatus at Bureau national de métrologie (BNM) and claimed uncertainty estimations from ±3 to ±5%.

Hohenauer [21] did an uncertainty assessment of their laser flash apparatus and stated an expanded uncertainty with thermal diffusivity measurement in the temperature range from 20 to 900°C of 3.98%.

3. Calculations via Wiedemann-Franz law

In some cases, it is more applicable to measure electrical conductivity respectively electrical resistivity. Heat transport and thus thermal conductivity through a metal or an alloy needs carriers. One has to distinguish between the component λ_e of thermal conductivity due to electrons and λ_l, which is the lattice contribution, due to phonons. Naturally for liquid metals and alloys, thermal conductivity is dominated by the electronic contribution. The total thermal conductivity would then be the sum of the components $\lambda = \lambda_e + \lambda_l$.

Thermal conductivity of liquid aluminum was examined at Graz University of Technology. Here the sole consideration of the electronic contribution gave promising results for the liquid phase [22]. A detailed derivation of the lattice-contribution to thermal conductivity can be found in the paper of Klemens [23].

An example when the lattice contribution has to be considered in the calculation of thermal conductivity for the Inconel 718 alloy is given in [24].

The Wiedemann-Franz law states that for conducting metals the electronic component of the thermal conductivity λ_e is

$$\lambda_e = L_0 \frac{T}{\rho(T)} \tag{10}$$

with $\rho(T)$ the temperature-dependent electrical resistivity and $L = \frac{\pi^2}{3} \cdot (k_B/e)^2 = 2.45 \times 10^{-8}\,\mathrm{W} \cdot \Omega \cdot \mathrm{K}^{-2}$ the (theoretical) Lorenz number.

Considering thermal expansion, the temperature-dependent electrical resistivity is

$$\rho(T) = \rho_{IG} \frac{d(T)^2}{d_0^2}, \tag{11}$$

with d_0 the diameter at reference temperature (room temperature), ρ_{IG} the electrical resistivity at initial geometry, and $d(T)$ the diameter at an elevated temperature T. To calculate thermal conductivity, it is therefore necessary to measure thermal volume expansion as well.

An estimation of thermal diffusivity $a(T)$ can be found by

$$a(T) = \frac{L_0 \cdot T}{c_p(T) \cdot D(T) \cdot \rho(T)} \tag{12}$$

with $c_p(T)$ the heat-capacity and $D(T)$ the temperature-dependent density. With the ohmic pulse-heating setup at Graz University of Technology (as explained later in this work), radial over longitudinal expansion is ensured (see, e.g., [25]). Considering Eq. (12) and radial expansion yields

$$a(T) = \frac{L_0 \cdot T}{c_p(T) \cdot D(T) \cdot \rho(T)} = \frac{L_0 \cdot T}{c_p(T) \cdot D_0 \rho_{IG}} \tag{13}$$

with D_0 the density at room temperature.

Thus, Eqs. (10) and (12) enable us to determine thermal conductivity and thermal diffusivity from ohmic pulse-heating experiments, and deliver results that are in the same range as results from Laser flash measurements, as shown in the thermal diffusivity intercomparisons NPL – Report CBTLM S30 [26]. With a variation of only 3%, our results were significantly close to the average determined.

The experimental setup at Graz University of Technology is described in the following section.

4. Measurements at Graz University of Technology

In ohmic pulse-heating experiments, the electric conducting sample is heated up by passing a large current pulse through it. Due to the resistivity of the material, the sample is heated up from room temperature to the melting point and further up through the liquid phase to the boiling point in a period of about 50–70 μs.

The specimen typically is in the shape of a wire, with diameters ranging from a few hundred micrometers up to some millimeters, rectangular shape for materials that cannot be drawn into wires, foils or tubes. As a consequence of the narrow time frame under which these experiments are performed, the liquid phase does not collapse due to gravitational forces, enabling investigations of the entire liquid phase up to the boiling point. In addition, the specimen can be considered to not be in contact with the surrounding medium, rendering the experiment to being a container-less method.

4.1. Setup

A typical pulse heating experiment consists of the following parts: An energy storage (mostly a capacitor or battery bank) with a charging unit, a main switching unit (e.g., high-voltage mercury vapor ignition tubes) and an experimental chamber with windows for optical diagnostics and the ability to maintain a controlled ambient atmosphere. Pulse heating experiments are mostly performed under inert atmosphere, e.g., nitrogen or argon at ambient pressure,

or in vacuum. The setup of the pulse-heating apparatus at Graz University of Technology is presented in **Figure 1**.

The setup has been explained in detail in previous publications [27–29].

4.2. Current and voltage measurement

The current pulse, which the sample is subjected to, is measured using an induction coil (Pearson Electronics, Model Number 3025). To measure the voltage drop, two Molybdenum voltage-knives are attached to the specimen. The voltage drop relative to a common ground is measured for both of the voltage-knives, allowing the measurement of the voltage drop between the two contact points of the sample and the respective voltage-knives (**Figure 2**).

4.3. Temperature measurement

A fast pyrometer provides temperature determination. The pyrometer measures the spectral radiance of a sample surface from which the temperature can be calculated using Planck's law.

$$L_{\lambda,B}(\lambda, T) = \frac{c_1}{\pi \cdot \lambda^5} \cdot \frac{1}{e^{\frac{c_2}{\lambda \cdot T}} - 1}, \tag{14}$$

with $L_{\lambda,B}(\lambda, T)$ the radiance emitted by a black body at temperature T and wavelength λ and the two radiation constants $c_1 = 2\pi \cdot h \cdot c^2$ and $c_2 = \frac{h \cdot c}{k_B}$ (h is the Planck's constant, c the speed of light, and k_B the Boltzmann constant). It has to be considered that nearly no real material is a perfect black body. The deviation from black body radiation is taken into account by emissivity $\varepsilon(\lambda,T)$. The ratio of radiation emitted by a real material therefore is

$$L_\lambda(\lambda, T) = \varepsilon(\lambda, T) \cdot L_{\lambda,B}(\lambda, T). \tag{15}$$

It has to be noted as well that the measured quantity of the pyrometer is a voltage signal $U_{Pyro}(T)$, which is dependent on measuring geometry, transmission of the optical measuring setup, width of the spectral range and detector sensitivity. When summarizing the majority of the temperature-independent quantities in a constant C, the pyrometer signal is

$$U_{Pyro}(T) = C \cdot \varepsilon(\lambda, T) \cdot \left(e^{\frac{c_2}{\lambda \cdot T}} - 1\right)^{-1} \tag{16}$$

4.4. Thermal diffusivity and thermal conductivity

With the obtained values of the time-dependent current $I(t)$, the time-dependent voltage drop $U(t)$, the specimen radius $r(t)$ and the surface radiation $L(t)$ it is now possible to calculate the desired thermal properties, i.e., thermal conductivity $\lambda(T)$, thermal diffusivity $a(T)$ as well as specific heat capacity $c_p(T)$. This has been shown briefly in the second section of this chapter and is thoroughly discussed in [30, 31].

The solid phase as well as the liquid phase data are fitted linearly (for the solid phase) and quadratically (for the liquid phase). In our publications (e.g., [22]) we give the coefficients for the

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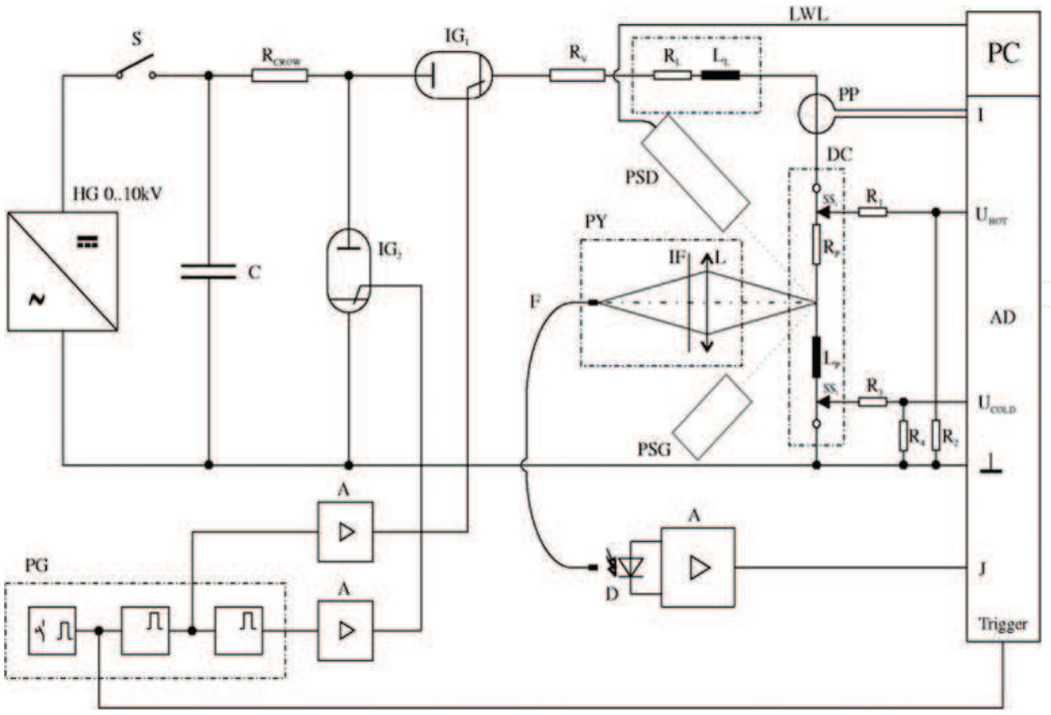


Figure 1. Schematic experimental setup. HG: high voltage power supply; S: switch for loading the capacitor bank C; R CROW: crowbar resistor; I G 1 : main ignitron; I G 2 : crowbar ignitron; R V : matching resistor; R C, L C, R S, L S : resistance and inductance of the circuit and/or the sample; R 1 – R 4 : voltage dividers; K E 1, K E 2 : knife-edge probes; PP: Pearson-probe; DC: discharge chamber; PY: Pyrometer; L: lens; IF: interference filter; F: fiber; D: photodiode; A: amplifier; PG: pulse generator; AD: analog-to-digital converter; PC: personal computer; I, U HOT, U COLD, J : measurement signals of current, voltages and intensity of radiation; PSG: polarization state generator; PSD: polarization state detector; LWL: light wire line.

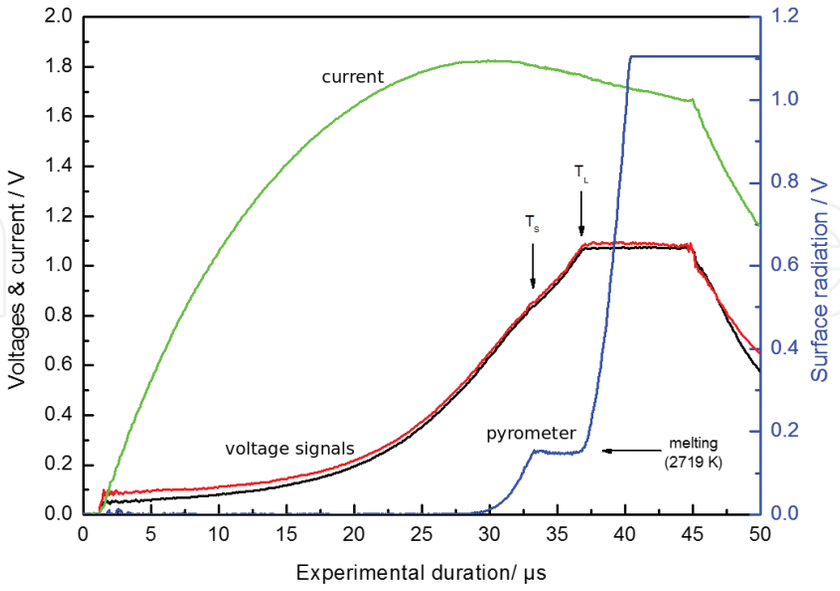


Figure 2. Typical raw measurement signals of the ohmic pulse-heating experiment performed on Iridium. The black line and red line are the voltage signals, the green line is the current signal and the blue line is the signal of the pyrometer. Note that solidus temperature (T_S) and liquidus temperature (T_l) are visible not only in the pyrometer signal, but also in the voltage signals.

linear fits as well as uncertainty assessments. The schematic data provided in this chapter are for aluminum; therefore, the temperature range is rather low. With the ohmic pulse-heating apparatus, it is also possible to examine high melting metals like tungsten, niobium and tantalum.

Figures 3 and **4** show typical results of thermal conductivity and thermal diffusivity determination with the ohmic pulse-heating apparatus for aluminum.

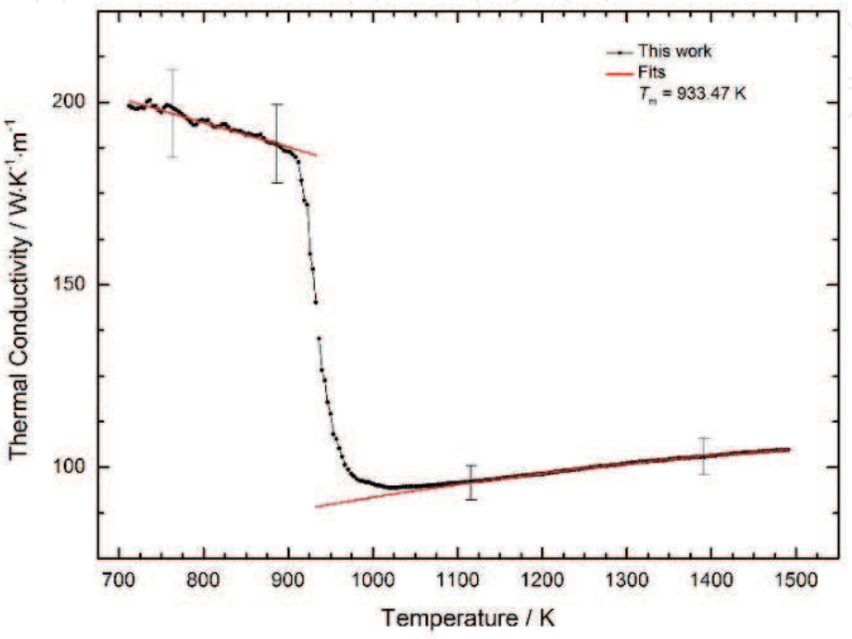


Figure 3. Results of thermal conductivity determination for aluminum. Data taken from [22].

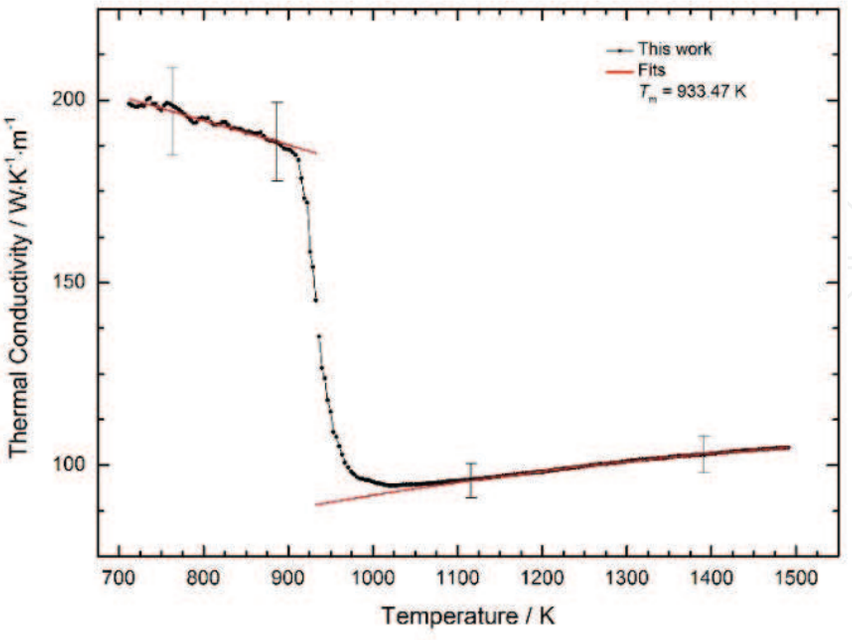


Figure 4. Results of thermal diffusivity determination for aluminum. Data taken from [22].

The data show the solid phase (up to about 900 K) and the liquid phase (up to 1500 K). Thermal conductivity in this case can be fitted quadratically with a positive slope in the liquid phase.

4.5. Uncertainty for the ohmic pulse-heating method

Uncertainties have been estimated according to GUM [32], with a coverage factor of $k = 2$ (95%).

Uncertainties for thermal conductivity $\lambda(T)$ for aluminum have been estimated ±6% in the solid phase and ±5% in the liquid phase. Uncertainties for thermal diffusivity $a(T)$ for aluminum have been estimated ±8% in the solid phase and ±5% in the liquid phase. See also [22].

5. Conclusions

A variety of common methods to determine thermal conductivity of liquid metals have been reviewed in this chapter. These methods can be classified into steady state, non-steady state, and transient techniques. However, not all of the reviewed methods are suitable for the liquid phase of high-melting metals.

To conclude this chapter, the methods that are suitable for the determination of thermal conductivity of high-melting metals in the liquid phase are summarized.

The laser flash method (LFM) is applicable also for high-melting metals, as the temperature range has been reported to be −120 to 2800°C. Uncertainties for this measurement technique range from ±3 to ±15% [16–19].

Another suitable method to determine thermal conductivity of even high-melting metals in the liquid phase is the ohmic pulse-heating method in combination with the Wiedemann-Franz law. This method can easily achieve temperatures of about 4000 K and higher and is therefore suitable for all high-melting metals (the metal with the highest melting point is tungsten with 3695 K). Uncertainties for thermal conductivity for aluminum have been estimated ±6% in the solid phase and ±5% in the liquid phase [22].

Especially in the liquid phase, where lattice contributions in the determination of thermal conductivity can be neglected, the ohmic pulse-heating method has been proven to be a very accurate method. This has been shown in an intercomparison with laser flash measurements in [26].

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