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Thermophysical property measurements of high temperature melts: results from the development and utilization of space

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Abstract
Accurate and precise thermophysical properties are required for numerical modelling, so that improved high temperature processes can be developed such as crystal growth of semiconductor materials and casting of engines and turbine blades. The microgravity environment, one of the tools of materials sciences, offers marked advantages for the measurements; the major benefits are the absence of convection and the assurance of containerless processing. This paper reviews not only past microgravity experiments dealing with thermophysical property measurements but also the efforts to measure thermophysical properties on Earth using techniques developed originally for space experiments. Thermophysical property measurement is one of the new fields of materials sciences triggered by working in space. An outlook into the space station era is also given with special emphasis on opportunities and challenges.

Keywords: thermophysical properties, high temperature melts, microgravity, containerless processing

1. Introduction

1.1. The need for thermophysical properties of high temperature melts

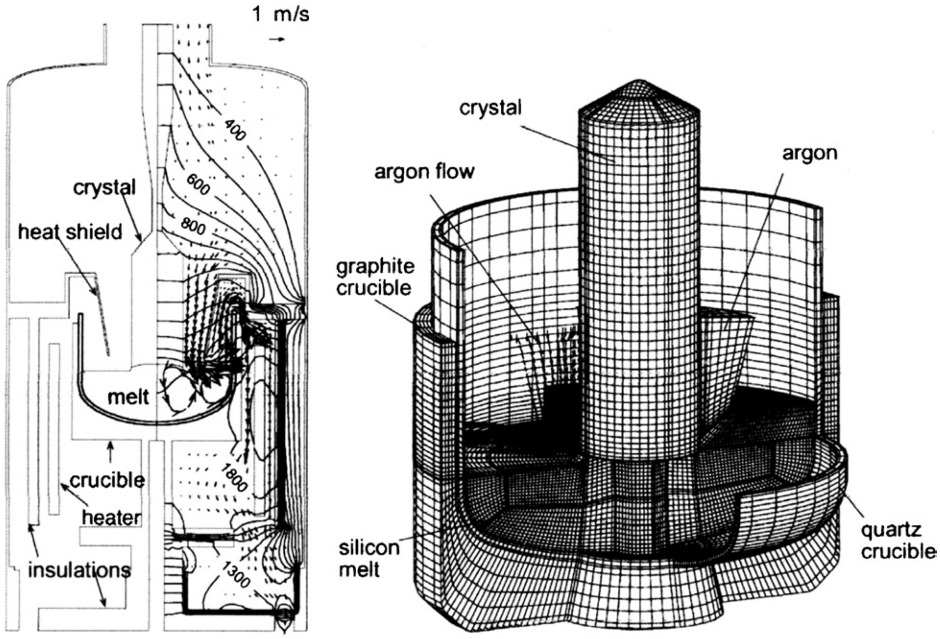
Modern society features the large scale exchange of information and the large scale transportation of people and goods. The former is supported by IT (information technology) and the latter by aerospace and automobile technologies. IT requires high speed data processing and high speed data transmission, whereas the aerospace and automobile technologies require high performance engines. From the materials science viewpoint, the former is supported by high quality semiconductor crystals and the latter by high performance engine materials, such as turbine blades. Both semiconductor crystals and turbine blades are produced from high temperature melts. In order to understand and control these high temperature processes, such as crystal growth and casting, computer modelling is one of the superior tools, which shows us the physics of these processes and how to improve processes and products [1, 2], as shown in figures 1 and 2.

In order to calculate temperature, flow and pressure fields of a high temperature process, the thermophysical properties of the molten state in particular are indispensable. A survey was carried out on the required thermophysical properties for these high temperature processes in Europe [3] and Japan [4]. The questionnaire in European countries covered mainly casting industries and in Japan semiconductor silicon industries, as shown in figures 3 and 4.

1.2. Characteristics of high temperature melts and use of microgravity conditions

It is difficult to measure thermophysical properties of high temperature metallic melts, because of the following characteristics:

- high temperature (buoyancy convection takes place easily)
- chemical reactivity (no crucible materials)



(*a*) (*b*)

Figure 1. Simulation of temperature distribution and flow velocity for silicon crystal growth: (*a*) calculated temperature and flow fields, (*b*) three dimensional grid for crucible, melt and inert gas blocks [1].

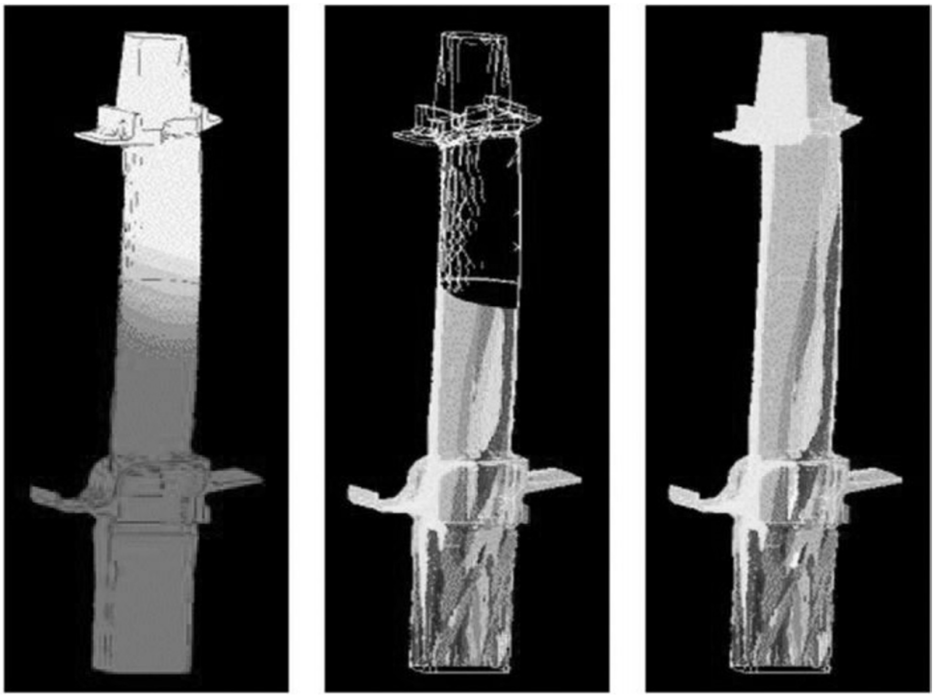


Figure 2. Simulation of temperature distribution in casting of a turbine blade [2].

- opaqueness (optical measurement is impossible)
- electrical conductivity in particular for molten metal and semiconductors (use of a metallic sensor is impossible).

In order to determine the thermophysical properties of high temperature melts, the development of new methods to overcome the above mentioned problems is required. One countermeasure against these problems is to use weightlessness (microgravity) conditions. The microgravity environment is featured as shown in figure 5. The suppression of buoyancy-driven convection allows mass and heat transfer mechanisms to be changed, i.e., there is neither mass transfer nor heat transfer due to buoyancy convection in microgravity. Thus, it is possible to the measure diffusion constant and thermal conductivity accurately without the effect of convection.

Thermophysical property measurements have been attempted using microgravity conditions. Measurement of the diffusion constant has been attempted in microgravity

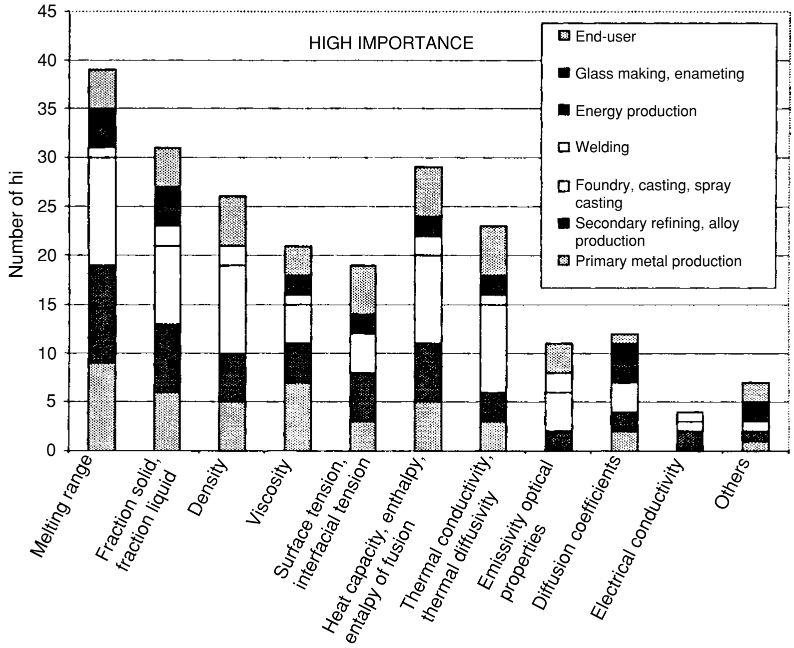


Figure 3. Required thermophysical properties in casting industries (in UK) [3].

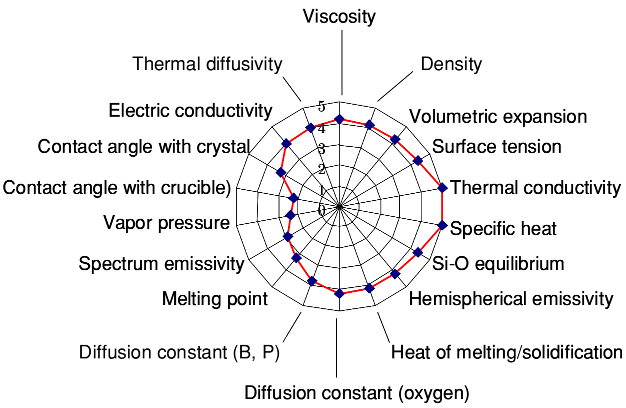


Figure 4. Required thermophysical properties for silicon industries (in Japan) [4].

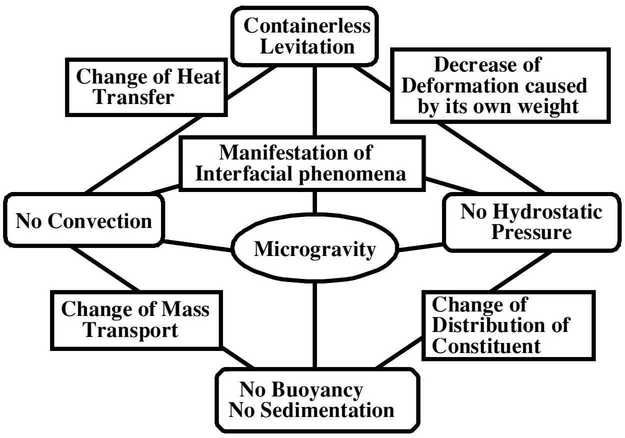


Figure 5. Characteristics of microgravity conditions.

conditions since the Skylab era [5]. It was tried on the SL-1, D1 and D2 missions using a Space Shuttle flight. It was found that the diffusion constant measured under microgravity was smaller than that measured on Earth [6, 7]. Limited numbers of thermal conductivity measurements have been reported for molten semiconductors on Earth, such as InSb and GaSb [8, 9]. There have been no direct measurements of thermal conductivity on GaAs and Si, except for attempts by Yamamoto *et al* [10] and by Yamasue *et al* [11]. A transient hot-wire method is a good tool to measure the thermal conductivity of a liquid directly. Although this method can be applied on Earth, the measurement time without the effect of convection is very short. If the transient hot-wire technique can be applied in microgravity conditions, the measurement accuracy can be improved, because the measurement time without buoyancy flow occurring can be prolonged. Thermal conductivity measurement using the hot-wire technique was first attempted in microgravity conditions for an organic liquid [12]. The transient hot-wire technique was applied to measurement of thermal conductivity of a molten compound semiconductor in microgravity for the first time by Nakamura *et al* [13]. Electrical insulation between the wire and the melt is the key to applying this technique to metallic melts.

Containerless levitation has long been thought to be particularly attractive in microgravity conditions. The aerospace agencies of USA, Germany, Canada and Japan have tried to develop their own levitation facility [14–17]. To take full advantage of the microgravity environment such as on board the Space Shuttle and the International Space Station, novel and unconventional techniques have to be developed. These are techniques for measuring surface tension, density, viscosity, specific heat and electrical conductivity of high temperature melts particularly using electromagnetic levitation [18–21]. The most important characteristic of containerless levitation is to prepare easily undercooled conditions. This attracts the interests of thermophysicists and material scientists and opens the door to a new category of science, i.e. the physics of undercooled

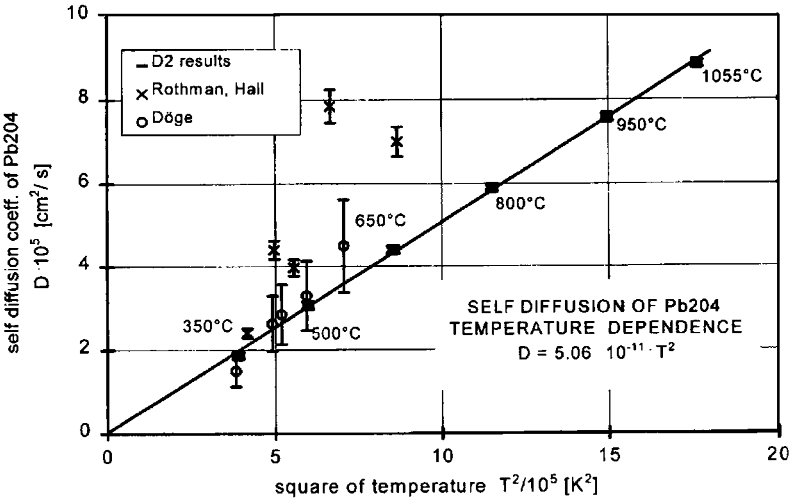


Figure 6. Self-diffusion coefficient of ^{204}Pb, measured during the Spacelab mission D2, and terrestrial data for comparison [7].

high temperature melts and rapid solidification of undercooled melts. Levitation facilities can be used even under normal gravity conditions. Although the gravitational force acts on droplets levitated on Earth, containerless levitation and preparation of undercooled conditions is possible such that thermophysical property measurements of undercooled melts can be attempted even on Earth. In most cases the microgravity environment improves the accuracy considerably; in some cases measurements on Earth are impossible. Although electromagnetic levitation on Earth has been known and used for more than 50 years, it has experienced a big boost and improvement from its use in space.

In this paper we present a brief review of the history of thermophysical property measurement triggered by the use of space and show examples of thermophysical property measurements both under microgravity conditions and on Earth. Also we discuss the perspective of thermophysical property measurement of high temperature melts.

2. Measurements of thermophysical properties of high temperature melts: history of the challenge

In this section we show how the microgravity condition is effective for thermophysical property measurements of high temperature melts. In section 2.1 measurements of the diffusion constant, Soret coefficient and thermal conductivity are described. These measurements require a container. In section 2.2 measurement of the electrical conductivity, density, thermal expansion, specific heat, surface tension and viscosity are discussed. Temperature range for measurement can be widened using a containerless technique. In section 2.3, the application of these measurement techniques to measurement under terrestrial condition is shown. In section 2.4, a perspective for thermophysical property measurement under microgravity is given.

2.1. Measurement with a container: diffusion constant, Soret coefficient and thermal conductivity

Measurements of diffusion constant, Soret coefficient and thermal conductivity require a container, generally a crucible, because the appearance of a free surface must be suppressed. A free surface with a temperature gradient causes Marangoni flow and a convection-free environment can be degraded even under microgravity conditions if a temperature gradient exists [22].

A thermodynamic system tends to maintain spatial homogeneity. Therefore, gradients in intensive variables cause heat or mass flows which try to eliminate these gradients. In linear irreversible thermodynamics, the flows are linearly related to the gradients [23]:

$$\begin{pmatrix} \vec{j}_c \\ \vec{j}_Q \end{pmatrix} = -\begin{pmatrix} D & S \\ Q & \lambda \end{pmatrix} \begin{pmatrix} \vec{\nabla} c \\ \vec{\nabla} T \end{pmatrix} \quad (1)$$

Two independent laws are derived from equation (1) if S and P are zero. They are Fick's law: $j_c = -D\nabla c$, defining the diffusion constant D, and Fourier's law: $j_Q = -\lambda\nabla T$, defining the thermal conductivity λ. The off-diagonal elements are usually very small. The existence of $S \neq 0$ is called the Soret effect; it describes thermomigration, i.e. a mass flow caused by a temperature gradient, while P describes a heat flow caused by a concentration gradient.

2.1.1. Diffusion constant. Diffusion measurements in microgravity utilize its convection-free environment. Because mass transport takes place more effectively by convection than by diffusion, diffusion measurements are prone to large errors whenever there is convection. Microgravity experiments on the self-diffusion of tin isotopes and lead were carried out by Frohberg *et al* [6, 7], who found that the diffusion coefficients as measured in space are 20–40% lower than those obtained from terrestrial experiments. The data are best fitted with a power law $D = KT^2$, which is in contradiction to the expected Arrhenius-type behaviour. Figure 6 shows data for lead, for example. This result has also provoked a question on the structure of high temperature melts. Frohberg's pioneering work triggered experiments to measure the diffusion constant under microgravity and other thermophysical property measurements.

In the present issue, the improvement of diffusion constant methods is discussed; Mathiak *et al* [24] discuss the effect

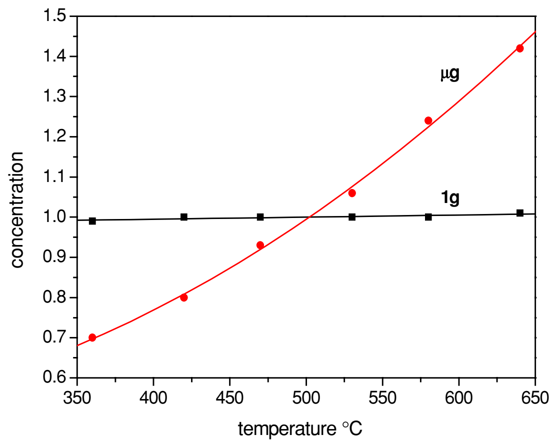


Figure 7. Soret effect of tin in cobalt at 500 °C [30].

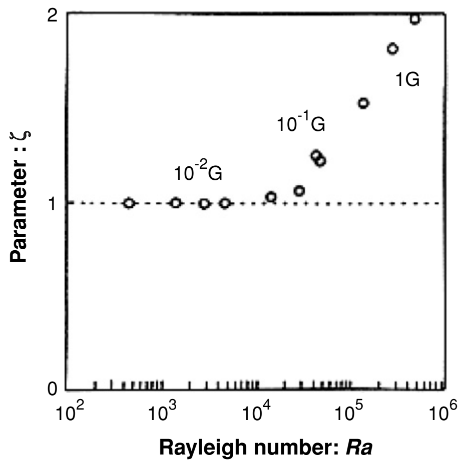


Figure 8. Influence of convective heat transfer on thermal conductivity measurements using a hot-wire technique [33].

of vibration during measurement, Masaki *et al* [25] explain the shear cell technique, Onishi *et al* tried to measure the interdiffusion constant for a mixed molten semiconductor system under a magnetic field [26]. Higuchi *et al* observed the short-range order of molten silicon over a wide temperature range including undercooled conditions [27]. Holland-Moritz proposed a new electromagnetic levitator to observe the short-range order of undercooled metallic melts [28]. Itami *et al* discussed concentration fluctuations in an immiscible system through electrical conductivity measurement [29].

2.1.2. The Soret coefficient. Under microgravity, the Soret coefficient S was determined by Malméjac and his co-workers for cobalt in tin by using a shear-cell technique [30]. Applying a temperature difference of 200 K cm^{-1}, they found a relative concentration difference of nearly 50%, whereas the same experiment performed on the ground yielded a homogeneous sample, i.e. 0% concentration difference. This is shown in figure 7. In recent years, there has been renewed interest in measurement of the Soret effect in microgravity by van Vaerenbergh and co-workers, who measured the Soret effect of organic solutions [31, 32].

2.1.3. Thermal conductivity. There is great demand for measurement of the thermal conductivity, as shown in figures 3 and 4. Thermal conductivity is strongly related to heat transfer within a melt and affects the solid/liquid interface shape and then the distribution of point defects in silicon crystals [1]. However, the thermal conductivity λ of a high temperature melt is one of the most difficult properties to measure, whereas the thermal diffusivity $\kappa = \lambda/(C_p\rho)$ can be measured by a laser flash method with reasonable precision on Earth, where C_p and ρ are the specific heat capacity and density of the liquid, respectively. The measurement error of these quantities is transferred when calculating thermal conductivity using thermal diffusivity. The main difficulty in performing accurate measurements of thermal conductivity or thermal diffusivity of liquids lies in the separation of the conduction process from convective effects. Transient methods have been used quite successfully, based on the fact that the characteristic time for the acceleration of the fluid by buoyancy forces is much longer than the propagation time of the temperature change caused by a strongly localized temperature gradient. Therefore, it is possible, in principle, by a suitable choice of the experimental conditions and geometrical design of the measuring cells, to perform convection-free measurements even on the ground. This is also dependent on the kind of liquid. Microgravity conditions can be used to further reduce convection and to extend the convection-free time regime.

The first measurements of the thermal conductivity of a high temperature melt in microgravity have been performed by Hibiya's group on InSb [13]. They applied the transient hot-wire method (THW) during a sounding rocket flight and in a drop tower experiment. In this method the temperature increase in the wire, generated by a heat pulse input at time zero, varies linearly with ln t,

$$\Delta T = \frac{q}{2\pi(\lambda_L + \lambda_S)} \ln t + C \qquad (2)$$

where q is the heat input per unit length, λ_L and λ_s are the thermal conductivity of the liquid and substrate, respectively. The constant slope of ΔT versus ln t permits the calculation of the thermal conductivity of the melt. If convection is present, the experimental temperature rise will not vary linearly with ln t, and the calculated apparent thermal conductivity will increase with time.

Essential points for applying this technique to electrically conductive melts are insulation of the wire from the melt and the suppression of Marangoni flow. Also, in order to withstand vibration during launch of the rocket and mechanical shock at the moment of landing in the drop shaft experiment, the hot wire was prepared on the substrate using a printing method.

Figure 8 shows the effect of gravitational acceleration on thermal conductivity measurement using the transient hot-wire method [33]. The dimensionless parameter ζ shows the contribution of convective heat transfer to total heat transfer; $\zeta = 1$ means that there is no effective contribution of convective heat transfer to the measurement. As shown in figure 8, the thermal conductivity of a metallic melt can be measured even under the condition where flow still remains, such as the $10^{-2}g$ condition created by a parabolic flight in an aircraft.

Recently, Nagai *et al* attempted to measure the thermal conductivity of molten silicon using a hot-disk method in short-duration microgravity [34].

2.2. Measurement without a container: electrical conductivity, density and thermal expansion, specific heat, surface tension and viscosity

Thermophysical properties of high temperature and highly reactive melts can be conveniently measured by containerless methods, such as electromagnetic levitation. These methods provide the purest environment possible and undercooled conditions. Since the surface of the liquid sample is not in contact with a wall, Marangoni convection will occur if there is a temperature or concentration gradient along the surface. Flow within a levitated droplet is discussed by Hyers in the present issue [35]. Therefore containerless techniques are only applicable to those problems where convection plays no role. Thermophysical properties of levitated samples have been measured in microgravity during two Spacelab missions, using the electromagnetic levitation facility TEMPUS [18, 36].

2.2.1. Electrical conductivity. Electrical conductivity is required for computer modelling of the electromagnetic processes of steel making and crystal growth. It is possible to measure the electrical conductivity of levitated melts using a non-contact, inductive method. Lohöfer and Egry successfully measured this for a molten Co–Pd alloy under microgravity [21]. The impedance of a coil surrounding the sample is influenced by the sample's electrical conductivity. For spherical samples and homogeneous magnetic fields, as available in microgravity, this relation is rather simple, whereas under terrestrial conditions much mathematical and engineering effort must be spent to extract the required information from the measured impedance [37, 38]. The complex impedance can be determined by measuring both current I and voltage U simultaneously. The electrical conductivity σ is of interest in its own right, but it also allows one to obtain the thermal conductivity λ through the Wiedemann–Franz relation, which is known to hold well for liquid metals [39]:

$$\lambda = L\sigma T \tag{3}$$

Here, L is a universal constant, the so-called Lorenz number, $L = 2.44\ \mathrm{W\ \Omega\ K^{-2}}$. Thus, electrical conductivity measurements provide an alternative way to determine the thermal conductivity with the extra bonus that they are free of convective effects.

2.2.2. Density and thermal expansion. Density is one of the basic thermophysical properties. The normalized temperature coefficient of density, i.e. thermal expansion, is one of the driving forces of buoyancy convection. The density and thermal expansion of levitated drops are determined by recording the visible cross section of the sample. The volume is calculated by assuming rotational symmetry. Since the mass of the sample is known and does not change, this yields the density. Typically, a resolution of $\Delta V/V = 10^{-4}$ is required. This can be achieved using sub-pixel algorithms for edge detection, curve fitting of the shape, and statistical averaging [19, 40]. Although such measurements can be performed on the ground [40], in microgravity the precision of the data is improved and the accessible temperature range is extended [19].

2.2.3. Specific heat. Fecht and Johnson developed a non-contact method to determine the specific heat in levitation experiments. It is a variant of non-contact modulation calorimetry, normally used in low temperature physics. The heater power input into a heating coil is modulated according to $P_\omega(t) = \Delta P_\omega \cos(\omega t)$, resulting in a modulated temperature response ΔT_ω of the sample. If heat loss is due to radiation only, i.e, the experiment is performed under vacuum conditions, and if the modulation frequency ω is chosen appropriately, a simple relation for the temperature variation can be derived:

$$\Delta T_\omega = \Delta P_\omega/(\omega C_\mathrm{p}) \tag{4}$$

from which the specific heat, C_p can be determined. A detailed description of the application of ac calorimetry in microgravity is given in this issue by Wunderlich and Fecht [41].

On the ground the levitated sample must be cooled in a stream of inert gas, because large levitation fields are necessary to overcome terrestrial gravity and this field inevitably heats the droplet.

2.2.4. Surface tension and viscosity. Viscosity and surface tension are conveniently measured by the oscillating drop technique [42, 43]. Liquid samples perform oscillations around their equilibrium shape. In microgravity this is a sphere, and in that case simple formulae can be used to relate the frequency ω and damping Γ of the oscillations to surface tension γ and viscosity η, respectively. They read:

$$\omega^2 = \frac{32\pi}{3}\frac{\gamma}{M} \tag{5}$$

and

$$\Gamma = \frac{20\pi}{3}\frac{R_0\eta}{M} \tag{6}$$

where M is the mass of the droplet and R_0 its radius. An advantage of this method is that surface tension can be obtained without density data, which is required for other conventional methods. The sample oscillations are recorded with video cameras. The presence of the gravitational field distorts the sample shape and, consequently, the oscillation spectrum, which makes a quantitative analysis difficult. In figure 9, oscillation spectra of a gold–copper alloy are shown, recorded on the ground and in microgravity [44]. As can be seen, both a splitting of the single frequency into five peaks and a shift to higher frequencies occur for the terrestrial measurement. The first effect can be attributed to the deterioration of the spherical symmetry, while the latter is due to the magnetic pressure acting on the sample's surface [43]. Measurement of surface tension is easier under microgravity than on Earth, because the above mentioned frequency splitting does not take place in microgravity. Measurement of viscosity can be done only in microgravity, whereas the electromagnetic input for positioning stimulates flow on Earth and then it is almost impossible to observe any decrease in oscillation on Earth [35].

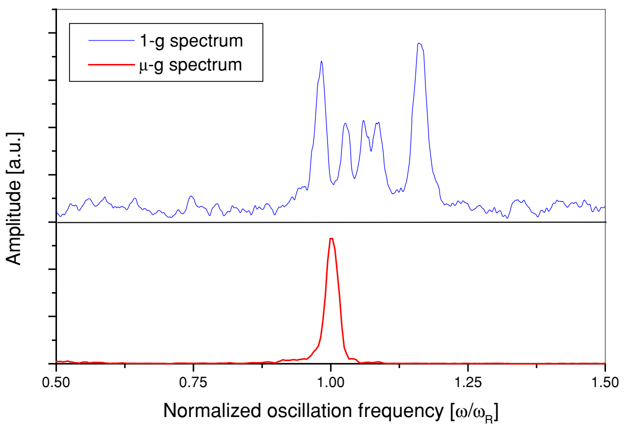


Figure 9. Frequency spectrum of an oscillating AuCu drop under 1*g* top) and microgravity (bottom) [44].

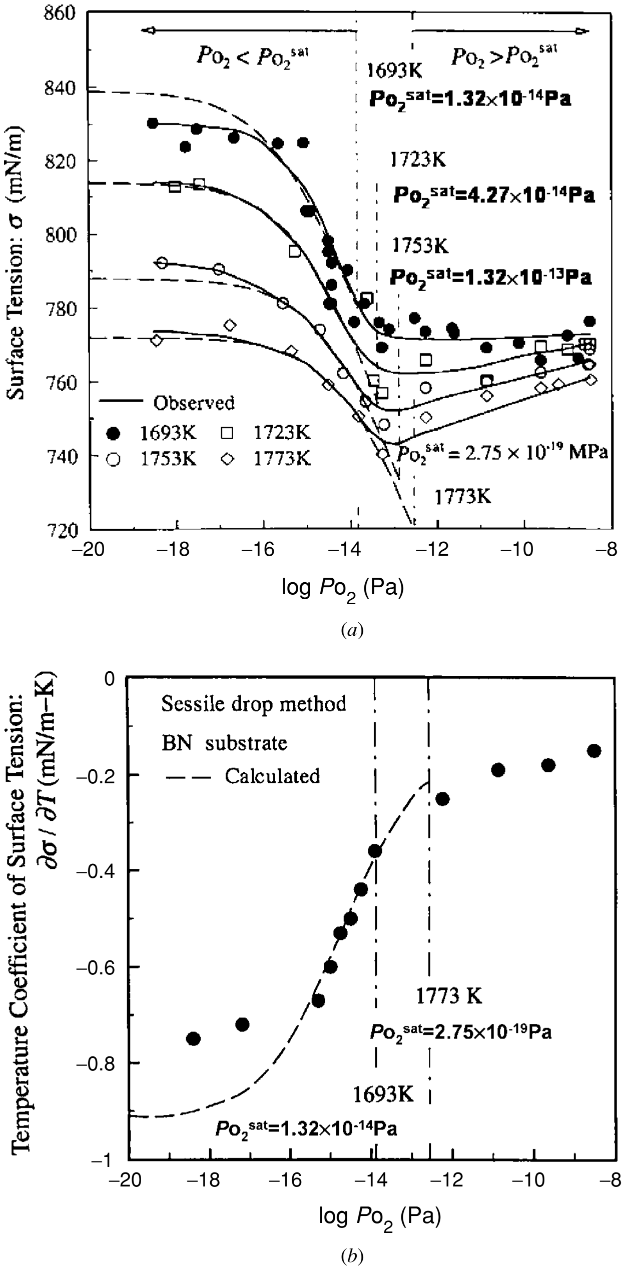


Figure 10. Surface tension (*a*) and its temperature coefficient (*b*) of molten silicon as a function of oxygen partial pressure for various temperatures [57].

3. Challenge on Earth

Triggered by thermophysical property measurements in microgravity, particularly measurement of the diffusion constant, lots of thermophysical property measurements have been attempted on Earth and in short-term microgravity conditions using a drop shaft or parabolic flights. In order to suppress convective mass and heat transport, a magnetic field has been applied to measurements of the diffusion constant [26, 45, 46]. The application of a magnetic field was also attempted for thermal conductivity measurement of mercury using a transient hot-wire method [47].

The existence of anomalous behaviour in the density of molten silicon just above the melting point has been reported [48]: the density of molten silicon abruptly increased or decreased just above the melting point. In order to confirm whether an anomaly really exists or not, a containerless method using electromagnetic levitation was employed, because the temperature range of measurement was extended into the undercooled region over the melting point. If the anomaly really exists, this must be observed even under the undercooled condition. Density measurement using the containerless method denied the existence of anomalous behaviour [49]. Egry *et al* gave a thorough discussion of improving the measurement technique for surface tension and viscosity [50].

Besides electromagnetic levitation, thermophysical property measurements using an electrostatic levitator have been carried out by Rhim's group at the California Institute of Technology [51, 52] and Ishikawa's group at the Japan Aerospace Exploration Agency [53, 54]. Ishikawa *et al* attempted to measure the thermophysical properties of refractory metals, and Paradis *et al* tried to measure the thermophysical properties of molten ceramics. The viscosity of high temperature melts can be measured using an electrostatic levitator.

Stimulated by research on the Marangoni flow of molten silicon in microgravity conditions, the measurement of surface tension of high temperature melts has shown great progress. The Surface tension of molten silicon has been measured using electromagnetic levitation [55, 56]. The use of a containerless method was effective in checking the existence of anomalous behaviour of the surface tension for molten silicon just above the melting point, as well as that for density. Since Marangoni convection of molten silicon shows a marked dependence on the oxygen partial pressure of the ambient atmosphere, measurements of surface tension and its temperature coefficient have been demanded. Mukai *et al* were the first to measure the surface tension of molten silicon and its temperature coefficient using a sessile drop method in a carefully controlled atmosphere with various oxygen partial pressures [57], as shown in figure 10.

Fukuyama *et al* measured the normal spectral emissivity of molten silicon precisely over a wide temperature range including the undercooled condition [58]. The viscosity of high temperature melts has been measured mainly by an oscillating cup method [59–61]. Sato *et al* measured the viscosity of molten silicon precisely and investigated the effect of crucible materials on measurement [61]. Recently, new ideas have been proposed, so as to improve thermophysical property measurement using a containerless method. One is measurement of surface tension and viscosity using a free-fall oscillating drop method. Although the duration of microgravity is very short (0.5 s) in the free-fall system on the laboratory scale (1.4 m), many oscillation signals can be obtained by using a small droplet. Since there is no input of external power during the free-fall period, the viscosity can be measured by analysing the decrement of oscillation [62, 63]. The other idea is superimposition of a static magnetic field on electromagnetic levitation. This can damp the oscillation of the metallic sample in the levitation coil to a great extent and then measurement of thermophysical properties can be improved [64].

Sensitivity analysis on thermophysical property measurements is important, because measurements are difficult and an intensive effort should be made on those properties, on which the results of numerical modelling depend markedly [65]. As for the sensitivity analysis for silicon crystal growth, Tsukada's group investigated the influences of the thermophysical properties of the melt and crystal on the nondimensional crystal pulling rate, i.e., the Peclet number $Pe = \rho_c C_{pc} r_c V_c / k_c$, and the deflection of the melt/crystal interface Δz, where ρ_c, C_{pc} and k_c are the density, specific heat and thermal conductivity of the crystal, respectively. V_c and r_c are the crystal pulling rate and crucible diameter, respectively. The results demonstrated that, concerning the thermophysical properties of the melt, Pe and Δz are relatively sensitive to emissivity. Concerning the crystal properties, Pe is more sensitive to thermal conductivity, while Δz is more sensitive to emissivity [66].

One of the measures to overcome the difficulty of measurements is a theoretical approach. A calculation based on thermodynamics was performed for surface tension by Tanaka's group [67].

4. Age of the International Space Station

4.1. Hardware design

In the past, the space environment has been considered to be a factory, where new functional, valuable materials should be manufactured, whereas scientific use of the microgravity environment, such as for thermophysical property measurement, was only a minor portion of all materials sciences. This has changed recently. The potential of microgravity for thermophysical property measurements and, vice versa, the potential of thermophysical property measurements for microgravity and, in particular, use of the Space Station, is now fully recognized. One of the outstanding Microgravity Application Promotion programs of ESA, THERMOLAB, is devoted entirely to high precision thermophysical property data of industrially relevant alloys, followed by an international program SEMITHERM for semiconductor melts. Consequently, the hardware necessary to perform such experiments is now being developed.

An electromagnetic levitator is under development as part of the Materials Science Laboratory. This facility, MSL-EML [68], is a joint European–German project, and is based on the TEMPUS Spacelab facility. It will be equipped with state-of-the-art non-contact diagnostic tools, like pyrometers, high-speed and high-resolution video cameras, and an infrared radiometer. MSL-EML will allow the kind of experiments described above to be performed. In addition, owing to its modular concept, new experimental concepts can be implemented at a later stage. MSL-EML will be accommodated in the European COLUMBUS module and will be operational, according to the present schedule, in 2007.

4.2. Opportunities and challenges

Most past microgravity experiments suffered from restricted access to the experiment and the limited time available for to perform it. The capability for real-time adjustment of the set-up and for repetitive series of experiments was very limited. With the advent of the International Space Station (ISS) and the development of new advanced facilities for thermophysical property measurements on board the ISS, some of these problems may be alleviated.

The advent of the ISS will be remove one big bottleneck, i.e. the operational time in microgravity. This creates the opportunity to perform systematic investigations and parametric studies, such as, for example, the dependence of surface tension on oxygen partial pressure. The challenge lies in the effective use of this precious resource. In the past, microgravity experiments had to work the very first time. As could be expected, this did not always happen. It should now become possible to optimize an experiment iteratively, by modifying both the procedure and the hardware, just like in ordinary laboratory physics. Although time for experiments should now be more easily available, other resources are not, such as crew time, video downlink, mass up- and download. In comparison to other types of experiments, like crystal growth, thermophysical property measurements have the advantage that they mainly produce data and do not require actual processed samples to be brought back to Earth. In addition, a single sample can be used for many different experiments. The limited crew time and real-time video imply that experiments must either become autonomous or must be controlled from the ground by telescience tools. The ultimate goal is to use the ISS routinely for benchmark experiments in the sense of an International Bureau of Standards in Space.

4.3. Fruits of the use of space

Historically, the measurement of thermophysical properties of high temperature melts was recognized as a hard job, particularly the diffusion constant, thermal conductivity and surface tension. However, the barrier was lowered by introducing a new environment, i.e. microgravity, a new technique and a new facility. The door to a new field of science has been opened. A typical example of this is the science of undercooled high temperature melts. Stimulated by this paradigm shift, thermophysicists are making great efforts in this new field continuously. Also, the requirements of industry will accelerate this trend. A new concept of measurement techniques and facilities is available for use. This is really one of the fruits of the development and utilization of space.

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