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Thermophysical Properties of Liquid Platinum[1]

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Material properties of liquid metals are inherently difficult to measure. Static measurements are difficult to make on most metals because of the typically high values of critical temperature and pressure, problems with sample-container contamination, and physical strength limits of high-pressure vessels. Data on thermophysical properties of metals are needed for a variety of applications, and measurements on most liquid metals are performed using dynamic techniques. Dynamic pulse heating experiments are typically performed on nanosecond to millisecond timescales, providing data that would not otherwise be obtainable. We use a resistive pulse heating method to reach high-temperature expanded liquid-metal states at a constant pressure. This technique can be used for a variety of metals and allows accurate data to be obtained over a wide range of temperature. Metallic wire-shaped samples (1×25 mm) are resistively heated in an inert gas atmosphere for a period of about 10^{-4} s by an almost-square current pulse ($\sim 15 \times 10^3$ A). Samples expand along an isobaric path, with remote diagnostics providing data on current, voltage, temperature, volume, and sound speed. These basic quantities are then used to calculate several derivative quantities. We report measurements of enthalpy, temperature, volume, electrical resistivity, and sound velocity of liquid platinum for temperatures from the melting point up to ~5100 K.

KEY WORDS: density; electrical resistivity; enthalpy; platinum; pulse heating; sound velocity; temperature.

1. INTRODUCTION

The thermophysical properties of most metals above the melting point must be determined using dynamic techniques. Dynamic methods avoid problems with sample containment and contamination, but at the expense

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of precision. Various time scales are used for resistive pulse heating, with the highest accuracy obtained typically with slow heating rates. Our measurements utilize a microsecond heating technique that we believe represents a good compromise between slower, more precise, techniques [1] that are not able to reach far into the liquid phase and much faster experiments.

Our experimental technique involves resistively pulse heating a cylindrical sample in a high pressure vessel. Diagnostics measure temperature, volume, current through the sample, voltage developed along a known length of the sample, and sound speed of the final state. These quantities can then be combined to obtain additional thermodynamic properties of liquid platinum. Experiments are performed in an inert gas atmosphere at high pressure to suppress boiling and allow higher temperatures to be reached than possible at one atmosphere.

Data on platinum are of interest for a variety of reasons. We found platinum to be a very stable and well-behaved material during pulse heating and believe it to be a good candidate for a standard material.

2. EXPERIMENTAL DETAILS

Cylindrical samples 0.76 mm diameter and 25 mm in length were chemically cleaned and polished. Initial density was taken as 21.4 $g \cdot cm^{-3}$, and purity as 99.97%. Samples were mounted on axis in a cylindrical high-pressure vessel with four windows, allowing optical diagnostics to be utilized. The pressure vessel was filled with argon gas at a pressure of 0.2 GPa for these measurements. Heating was accomplished by discharging a large capacitor bank and allowing the current pulse to pass through the sample. This current pulse is roughly a square wave with amplitude adjustable to ~ 20 kA and length greater than 10 μs. For these measurements current through the sample was measured using a high-precision current transformer. Voltage developed between two contacting probes was measured with a high-impedance shunt circuit together with a current transformer. These electrical diagnostics allow enthalpy to be calculated as a function of time from

$$H(t) = \int_{t_0}^{t} I(t)\, V(t)\, dt \tag{1}$$

Of all quantities measured, enthalpy is the most accurate, with an uncertainty of $\pm 2\%$.

Volume is measured using a shadowgraph technique combined with an image-converter streaking camera. This system yields time resolved records of sample diameter, which may then be converted to volume or

density. Volume measurements are accurate to $\pm 3\%$. Measured volumes may be combined with voltage and current to calculate volume-corrected electrical resistivity. This is done using the equation

$$\rho_{el}(t) = A(t)\, R(t)/l \tag{2}$$

where $A(t)$ is the changing sample cross-sectional area, l is the voltage probe spacing, and $R = V/I$ is the sample resistance.

Temperature is measured using a fast optical pyrometer. The melting plateau for platinum was just within the sensitivity of this device. Temperatures are calculated from ratios of detected intensities at temperature T to that T_m at the melting point and are measured at several visible wavelengths. Measurements agree to within the experimental uncertainty of $\pm 5\%$. Results shown in this paper are for $\lambda = 700$ nm.

Sound speed across a sample diameter was measured with a noncontacting technique as described previously [2]. This method yields sound speed at the end point of an experiment, when final enthalpy is reached. Values for sound speed are accurate to $\pm 5\%$.

3. RESULTS

Measured thermophysical properties for platinum are summarized in Table I. All values shown are referenced to 300 K and are along the

Table I. Thermophysical Properties of Liquid Platinum[a]

H (MJ·kg^{-1})	T (K)	V/V_0	ρ_{el} ($\mu\Omega$·m)
0.398 (l)	2042	1.11	0.96
0.40	2075	1.12	1.02
0.45	2290	1.14	1.04
0.50	2500	1.16	1.08
0.55	2750	1.19	1.11
0.60	3015	1.20	1.13
0.65	3240	1.22	1.16
0.70	3475	1.23	1.18
0.75	3700	1.25	1.19
0.80	3925	1.27	1.22
0.85	4160	1.29	1.25
0.90	4375	1.32	1.30
0.95	4635	1.34	1.32
1.00	4850	1.35	1.33
1.05	5100	1.39	1.39

[a] $\rho_0 = 21.4 \times 10^3$ kg·m^{-3}; $V_0 = 4.67 \times 10^{-5}$ m^3·kg^{-1}.

0.2-GPa isobar. Higher-temperature data may be obtained by going to a higher-pressure isobar. Sound speeds are not shown in this table.

Shown in Fig. 1 are our results for enthalpy, plotted as a function of temperature for the liquid phase. The linear least-squares fit to these data yields

$$H = 2.1197 \times 10^{-4} T - 3.4451 \times 10^{-2} \tag{3}$$

for $2042 \leqslant T \leqslant 5650$ K, and with enthalpy in $\mathrm{MJ \cdot kg^{-1}}$. This fit yields a C_p value of $211.9\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$. Other measured values are $186\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$ of Chaudhuri et al. [3] and $250\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$ of Gathers et al. [4], and the recommended value of Hultgren et al. [5] is $178\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$. In Fig. 1, we also show the data of Gathers et al. [4]. The beginning of melt is known from pyrometer records and is $H_s \approx 0.274\ \mathrm{MJ \cdot kg^{-1}}$. The end of melt is also known from pyrometer records, to be $H_l \approx 0.398$, yielding a heat of fusion of $0.124\ \mathrm{MJ \cdot kg^{-1}}$. This value compares favorably with that of Chaudhuri et al. [3] of $0.114\ \mathrm{MJ \cdot kg^{-1}}$, that of $0.14\ \mathrm{MJ \cdot kg^{-1}}$ of Gathers et al. [4], and that of $0.128\ \mathrm{MJ \cdot kg^{-1}}$ of Lebedev et al. [6].

In Fig. 2 are shown our results for volume ratio V/V_0, plotted against enthalpy. Shown for comparison are the results of Gathers et al. [4]. The linear least-squares fit to our volume data is

$$V/V_0 = 0.39607H + 0.96049 \tag{4}$$

for $0.398 \leqslant H \leqslant 1.05\ \mathrm{MJ \cdot kg^{-1}}$.

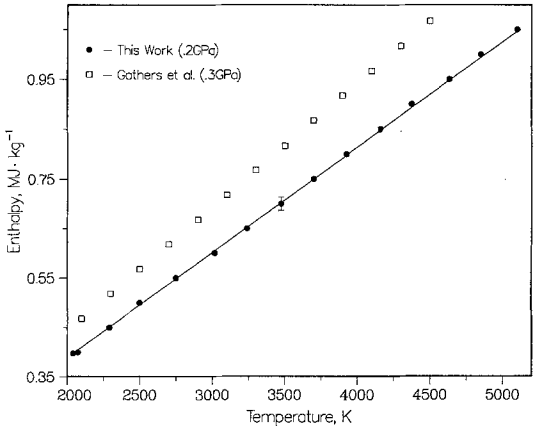

Fig. 1. Enthalpy as a function of temperature for liquid platinum.

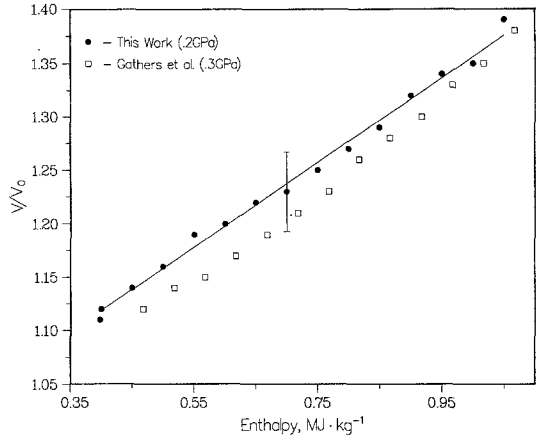

Fig. 2. Volume ratio V/V_0 for liquid platinum plotted versus enthalpy, where $V_0 = 4.673 \times 10^{-5}\ \mathrm{m^3 \cdot kg^{-1}}$.

Electrical resistivity for platinum may be calculated as described above, and the results for the liquid phase are shown in Fig. 3, along with those of Gathers et al. [4]. The linear least-squares fit to our resistivity data is given by

$$\rho_{el} = 0.536H + 0.7828 \tag{5}$$

with ρ_{el} in $\mu\Omega \cdot \mathrm{m}$ and $0.398 \leqslant H \leqslant 1.05\ \mathrm{MJ \cdot kg^{-1}}$.

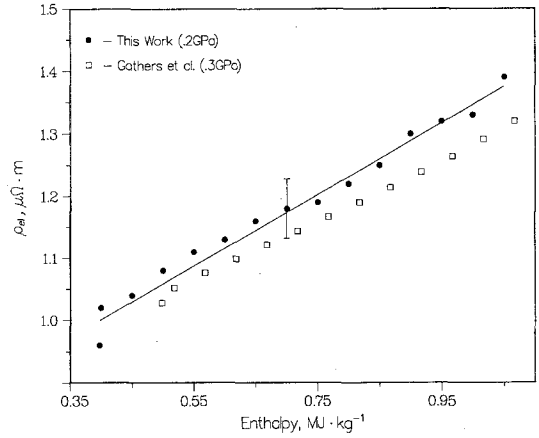

Fig. 3. Electrical resistivity as a function of enthalpy for liquid platinum.

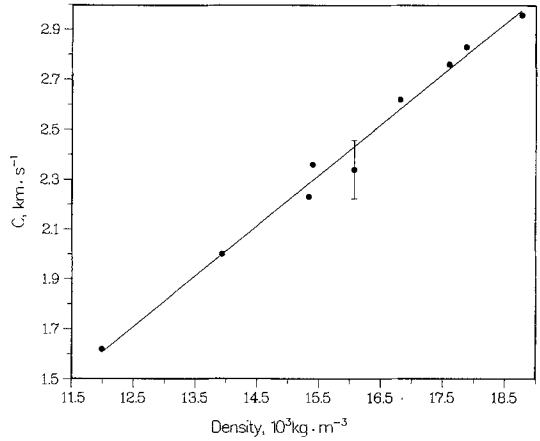

Fig. 4. Measured sound velocities for liquid platinum as a function of enthalpy.

Several sound speed experiments have been performed on liquid platinum, and the results are presented in Fig. 4; no literature values were found for comparison. Platinum was a very stable and well-behaved material under pulse heating, and sound speed measurements were straightforward. Results for platinum are best fit by

$$C = 0.2025\rho - 0.8213 \tag{6}$$

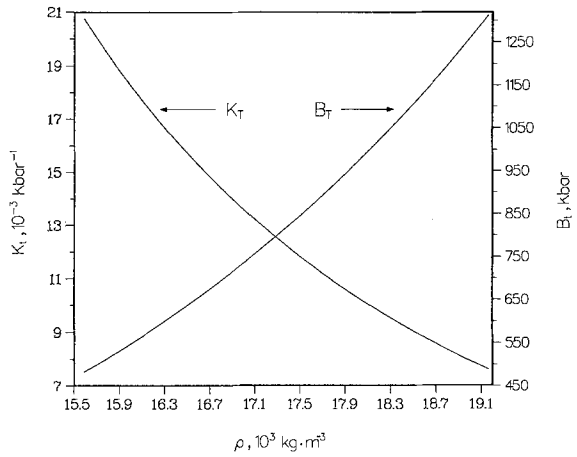

Fig. 5. Isothermal compressibility and bulk modulus as a function of density for liquid platinum.

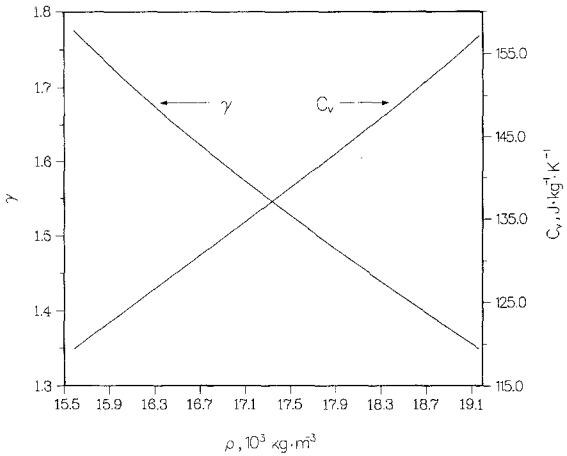

Fig. 6. Specific heat at constant volume and thermodynaic γ as a function of density for liquid platinum.

with C in km · s^{-1}, for $11.99 \leqslant \rho \leqslant 18.77$ g · cm^{-3}. Because platinum was so stable in the liquid phase, we were able to make sound speed measurements to densities lower than those reported in Table I. As observed for many other liquid metals, sound speed is linear with density.

4. CONCLUSIONS

Measurements have been made of several fundamental thermophysical properties of liquid platinum. From these properties other quantities may be calculated, such as Grüneisen gamma, adiabatic and isothermal compressibilities and bulk moduli, and thermal expansion coefficient. Shown in Fig. 5 are the calculated values of isothermal compressibility and bulk modulus, and in Fig. 6 calculated values for specific heat at constant volume and thermodynamic $\gamma = C_p/C_v$.

Because platinum was a very well-behaved material under pulse heating, we obtained a high accuracy in our measurements. Our results are compared with other measurements where possible, but we were unable to find extensive data on liquid platinum in the literature.

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