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HIGH TEMPERATURE SOUND SPEED MEASUREMENTS IN EXPANDED LIQUID TANTALUM

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ABSTRACT

Cylindrical samples of tantalum are resistively pulse heated to high temperature states along an isobaric path by capacitive discharge in a high pressure inert gas atmosphere. Using this technique samples may be heated to temperatures up to 10,000 K at pressures up to 1.0 GPa. The transient (10^{-4} s) heating technique is employed to overcome stability problems that prevent these measurements from being made statically.

Tantalum has been studied previously by Berthault (1986), Gallob (1979), Lebedev (1976), and Shaner (1979) and some thermophysical properties are well known over the accessible range. Our measurements are complemented by the additional capability to measure sound speeds in the hot expanded sample. Results of such measurements on tantalum at temperatures up to ~6000 K are presented along with several other quantities calculable from the sound speed data.

The largest disagreement among the various groups that have investigated tantalum at high temperature appears to be in the temperature scale. We report our recent temperature measurements with an improved optical pyrometer.

INTRODUCTION

The thermophysical properties of liquid metals are of interest for several reasons. These include the empirical design and modeling of exploding wires, foils, and fuses. Such properties also provide the necessary phenomenology for understanding fluid metals.

The extreme conditions under which such measurements must be made are dictated by the location of the thermodynamic critical point. The critical point is low enough in pressure and temperature for only a few metals (Hg, Cs, Rb, and K) to allow the use of static high pressure techniques. Other metals must be studied around their critical points by dynamic techniques such as shock compression or pulse heating.

We use a pulse heating method in which our sample is made to expand along an isobaric path (IEX). Details of this method are presented by Gathers (1976). We have extended the experimental capabilities by the addition of a sound velocity measurement. During the course of an experiment, enthalpy, temperature, specific volume, and sound speed are measured. From these fundamental quantities, other properties may be calculated as shown by Hixson (1986).

Recently we have constructed a new optical pyrometer using linear rather than logarithmic amplifiers, and here we report on revised temperature measurements in tantalum. Results on sound speed measurements in tantalum are also presented.

EXPERIMENTAL DETAILS

Temperature Measurements: A new optical pyrometer has been constructed to check previous results on Ta and other materials. This instrument is based on linear operational amplifiers and transient digitizers rather than the logarithmic amplifiers and oscilloscopes used previously. The use of linear amplifiers means that some provision must be made for different levels of gain because the intensity of light being measured can vary over a wide range. For our measurements on Ta the amplifiers were found to be linear to better than .5%, and two gain levels were chosen. The location of the melt plateau at T_m = 3270 K was used to calculate temperatures for the high gain channel, used for low light levels. The high gain channel will eventually saturate the transient recorder, and the highest temperature point is then used as a tie point for the low gain channel. The low gain channel then records the maximum temperature reached in the experiment. For the temperatures reached in these experiments two gain levels work well, but for higher temperatures we have the capability to go to more gain levels.

Temperatures were measured at 600 and 700 nm, and in these experiments the results from the two wavelengths were indistinguishable. Results are presented in Table I and Fig. 1 for the 700 nm channel. These points represent many shots with excellent shot-to-shot reproducibility. The least squares fit to our data is represented by

$$H = (2.66 \times 10^{-4})T - .148 \quad ,$$

where H is enthalpy in MJ/kg, T is temperature in K, and the standard error estimate is 0.0094. The agreement with previous measurements is reasonably good except for the results obtained previously with the IEX using our old pyrometer. Other properties measured previously with the IEX remain the same, and the above temperature fit allows previously calculated quantities to be corrected.

There are several possible sources of errors in the temperature measurement. Some of these can be estimated reliably, and others are more difficult to quantify. Instrumental uncertainties are less than 2% including non-linearities in hardware. Probably the largest source of uncertainty is the assumption that sample surface emissivity is constant with temperature. We intend to explore methods of quantifying this problem in the future, but for now can only estimate the magnitude of this effect. Overall uncertainty in temperature measurement is estimated at ±5%.

SOUND VELOCITY MEASUREMENTS

A technique described elsewhere is used to measure sound speed in the expanded liquid sample. Such measurements are very difficult to perform on liquid metals, even at low temperature, and especially difficult in a material that melts at 3270 K. Sound speeds in Ta were more difficult than our previous measurements in Pb for several reasons. First the high melting point can lead to sample motion while it is still in the solid state, and our technique depends upon the sample staying in its initial position. Second the relatively high conductivity of Ta compared with that for Pb, means that it is more difficult to heat with our constant current source.

We used a smaller sample diameter which gives us a smaller "target" for our pulsed laser.

The sound velocity measurement is done after heating has stopped and the sample is in an equilibrium end state. This means that we can obtain only one sound speed measurement per shot, and so a large number of shots were performed. Results are listed in Table II and shown in Fig. 2 for $0.7 \leq H \leq 1.7$ MJ/kg. The least squares fit to our data is

$$c = 0.2696\, \rho - 0.6147 \quad ,$$

where c is sound speed in km/s, ρ is density in g/cm^3, and with a standard error estimate of 0.021. No other data exist for acoustic velocity in fluid tantalum below normal density.

Data were taken only up to an enthalpy of 1.7 MJ/kg because this appeared to represent the upper limit of stable heating. Fast framing camera sequences show a loss of long term stability at around H = 1.7 MJ/kg, possibly due to the onset of boiling. Because heating takes place quickly, it is possible to overshoot the liquid-vapor coexistence curve and reach metastable superheated liquid states. This possibility will be examined in future work.

DISCUSSION

Thermophysical properties of Ta, excluding sound speeds, have been measured previously by Berthault (1986), Gallob (1979), Lebedev (1976), and Shaner (1979) using transient pulse heating methods. The results of these measurements agree very well in all properties except the temperature scale. The temperature scale reported by Shaner (1979) was later corrected by Gathers (1983) for systematic errors in the calibration. The convenience of a logarithmic amplifier is more than offset by the difficulty of calibration. Therefore we have abandoned that technique in favor of linear amplifiers.

The measurement of temperature as a function of enthalpy allows a direct determination of the specific heat at constant pressure. The value of C_p is very sensitive to the accuracy of temperature measurements, since enthalpy can typically be measured with high precision (~2%). Previously measured values of C_p for tantalum show it to be roughly constant above melt, with measurements ranging between a high of 326 J/kg.K and a low of 210 J/kg.K. The high value was determined using our IEX technique with the old optical pyrometers based upon logarithmic amplifiers. The low value is that of Berthault et al., using a similar pyrometer. Our new value, based upon this work, is 256 J/kg.K, which is in reasonable agreement with other workers.

Our sound speed data for liquid Ta shows linear behavior with density similar to that observed for Pb. In the case of Pb there were other results to compare with in a range where we overlapped static data. For Ta we were unable to find any data for sound speeds in the liquid. As was done for Pb by Hixson (1986), it is now possible to calculate other properties of Ta based upon the sound speeds and other quantities measured with the IEX technique.

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TABLE I

H (MJ/kg)	T(K)
0.72	3270
0.75	3500
0.85	3900
0.90	4100
0.95	4300
1.0	4500
1.1	4900
1.2	5300
1.3	5700
1.4	6000
1.5	6400
1.6	6800
1.7	7150

TABLE II

C(km/s)±7%	ρ(g/cm^3)±3%
2.49	11.49
2.51	11.63
2.56	11.76
2.63	12.10
2.73	12.30
2.76	12.62
2.78	12.67
2.87	12.90
2.99	13.21
3.08	13.69
3.15	13.85
3.23	14.35
3.28	14.49

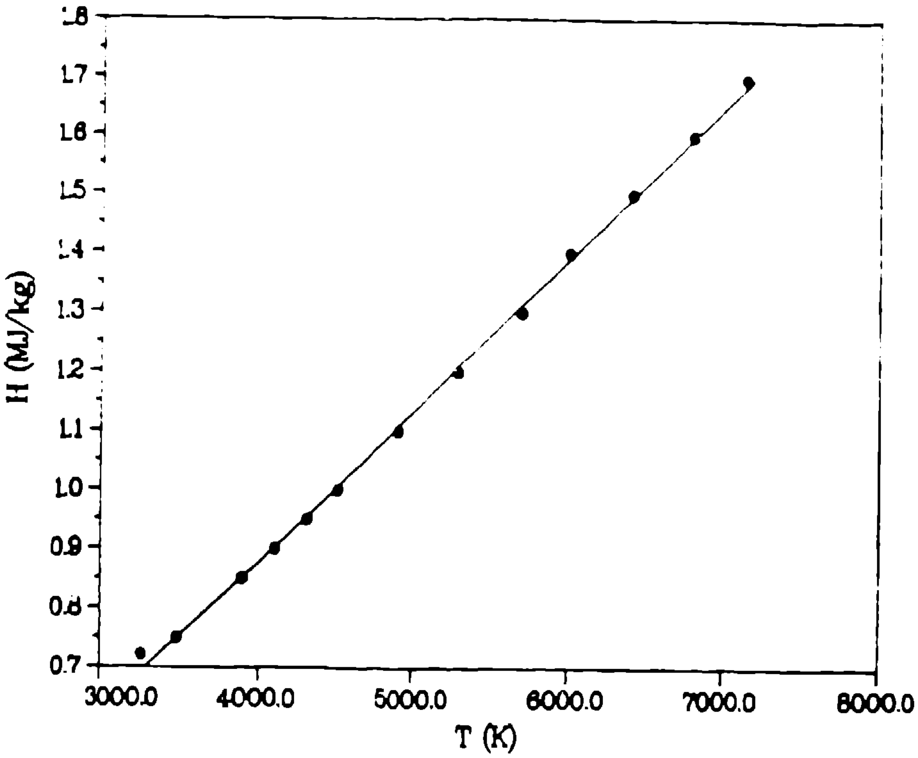

Figure 1. Enthalpy as a function of temperature obtained with an improved pyrometer.

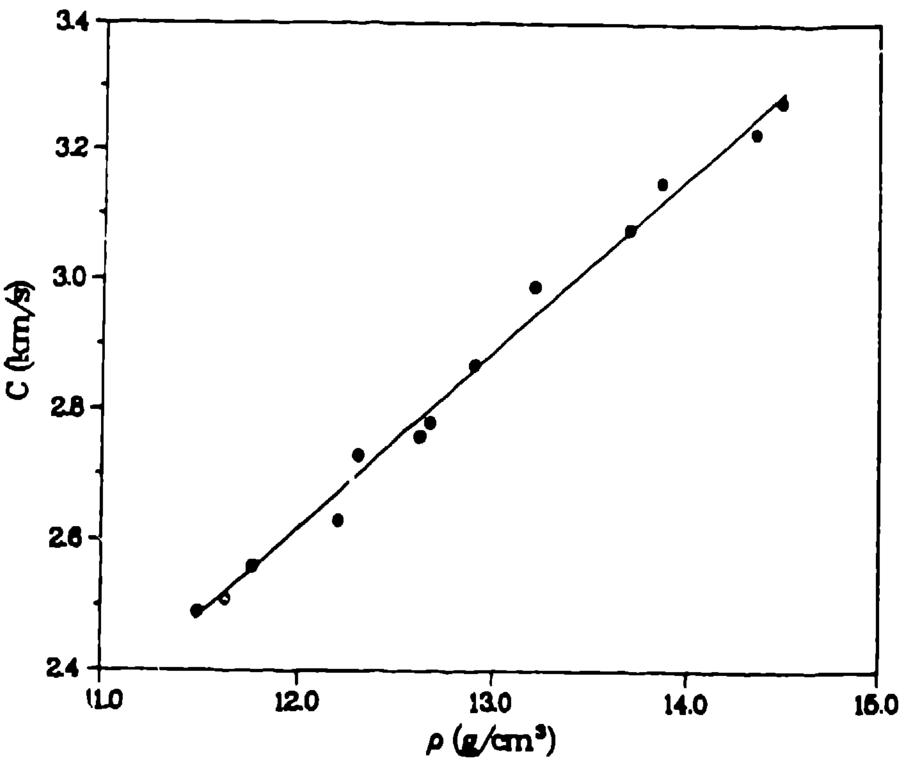

Figure 2. Sound speed plotted as a function of density for liquid tantalum.