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Sound Speed in Liquid Lead at High Temperatures[1]

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A dynamic technique, the isobaric expansion experiment (IEX), is used to reach high-temperature and pressure states in liquid lead. A unique technique is described for making sound-speed measurements once a final equilibrium end state is obtained. Data over an extended density range are presented. The sound speed in liquid lead over this range appears to vary linearly with density and has no dependence on temperature within our experimental precision (±7%).

KEY WORDS: dynamic technique; high pressure; high temperature; lead; sound speed; thermophysical properties.

1. INTRODUCTION

The measurement of thermophysical properties of liquid metals by conventional static techniques has necessarily been limited to relatively low temperatures and pressures. The major limiting factors in high-temperature static work are the loss of mechanical strength in the containment vessel and the diffusion or reaction between container and sample which can occur on the long time scale of such experiments.

To achieve very high-temperature states (~ 10,000 K) at high pressure (~ 1 GPa) in a liquid metal, a dynamic technique must be used. The isobaric expansion experiment (IEX) is such a dynamic technique, taking place over a time interval of approximately 10^{-4} s. During a typical experiment, several thermophysical properties such as the specific volume, enthalpy, and temperature along an isobaric path are measured. From these quantities, the specific heat at constant pressure and the coefficient of thermal expansion may be determined.

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This is a large amount of thermodynamic information, which can be obtained from a single experiment. A conceptually simple way to augment further the above data is to measure the sound speed along the isobaric heating path and thus obtain sound speed at many values of the independent variables [1].

In addition, the possibility exists for exploring other liquid-metal phenomena such as the determination of the thermodynamic critical point, the metal–insulator transition, and the liquid–vapor coexistence curve.

Data of the kind produced by the IEX are useful in a number of applications. These include the empirical design and modeling of exploding wires, foils, and fuses. They also provide the necessary phenomenology for liquid-metal theory.

2. EXPERIMENTAL TECHNIQUE

Measurement of sound speed in a system at high temperatures and pressures is not simple and must be done remotely. A technique for producing sound waves in liquid-metal samples in the IEX geometry using a low-energy laser light pulse focused onto the side of the sample has been discussed previously [2]. The emergence of the sound wave at the side of the sample opposite the source is the difficult part of the measurement technique, and several schemes for detecting this have been attempted [1–3]. Recently we have found a very simple scheme, based on a shadowgraph technique, for detecting this sound-wave arrival. The sonic wave arriving at the free surface of the sample causes a small amount of surface motion. Such motion causes a low-amplitude stress wave to move away from the sample surface into the surrounding high-pressure gas. The resulting index of refraction gradient associated with this stress wave in the gas causes a "shadow" to appear on our normal volume line-of-sight streak. By extrapolation of this shadow back to the image of the wire surface, we can measure the transit time through the sample, and from the known sample diameter the average speed may be calculated.

This technique was initially performed with a surrounding gas pressure of about 0.01 GPa [1]. We have now extended our measurements to pressures of 0.1, 0.2, and 0.3 GPa. The shadowgraphs at these pressures are of a higher quality than those obtained at low pressure. The majority of experiments have been performed at 0.1 GPa, and only one data point per experiment is obtained. The sound-speed measurement is done late in time in the experiment, after the heating pulse is completed and the stable end state has been reached.

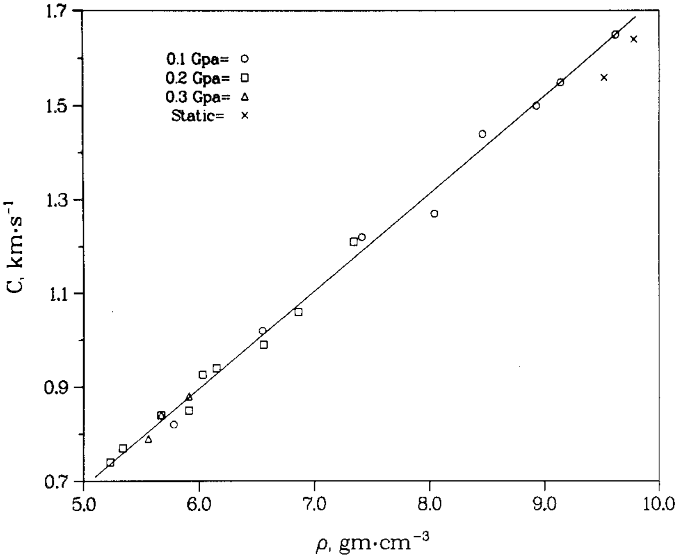

Fig. 1. Sound speed as a function of density for lead. The solid line is a least-squares fit to the data at all pressures.

3. EXPERIMENTAL RESULTS

Measured sound speeds in liquid lead are shown in Fig. 1 for densities ranging between 5×10^3 and 5×10^4 $\mathrm{kg \cdot m^{-3}}$. The data appear to be linear in this density range. Experiments at all pressures are shown in this plot and there does not seem to be any dependence on pressure. Static data are shown in Fig. 1 also, and the agreement with our data is excellent [4].

4. DISCUSSION

From the experimental results, we find that within our experimental uncertainties ($\pm 7\%$) the sound speed depends only on the density. This is true for pressures from 0.1 to 0.3 GPa and temperatures up to 5300 K. The major source of error in the sound-speed measurement is in the measurement of the sample diameter, and this uncertainty then increases when the diameter is squared to calculate density.

Our least-squares fit to the data at all pressures is

$$C = 0.2084\,\rho - 354.0 \tag{1}$$

where C is in $\mathrm{m \cdot s^{-1}}$, and ρ is in $\mathrm{kg \cdot m^{-3}}$. The standard error estimate calculated with this fit is 21.9 m · s^{-1}. As seen in Fig. 1, the data taken at 0.2 and 0.3 GPa extend to low values of density, while the data at 0.1 GPa were taken only at higher values of density. Sound speeds are measured after the sample has fully expanded and reached a stable end point of thermodynamic equilibrium. Since only one sound-speed datum is measured per experiment, it takes several experiments at each pressure value to characterize an isobar. Figure 2 is a difference plot for our data relative to the least-squares fit.

At the present time, extension of sound-speed measurements to even lower values of density is proceeding, but with difficulty. At expansions above about 2.2-fold, the gas disturbance generated by the ruby laser pulse has time to move around the sample and into our line of sight, obscuring the gas disturbance produced by sound-wave emergence from the sample. The problem occurs because as we increase the pressure in the containment gas, its sound speed increases. At 0.3 GPa the sound speed in argon is above 10^3 m · s^{-1}, and this is greater than the sound speed in high-temperature liquid lead.

Several approaches are being explored to try to solve this problem. An especially promising approach is the use of a VISAR velocity interferometer for detecting the onset of surface motion at sound-wave emergence. The extension to larger expansions is important in order to

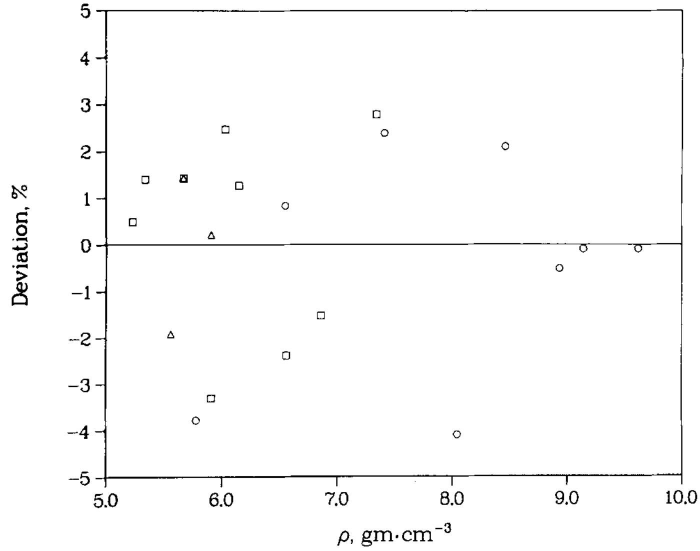

Fig. 2. Deviation of sound-speed data from the least-squares fit given by Eq. (1) for lead as a function of density.

look for possible deviations from the linear behavior leading to a change in the slope of C vs ρ. Such a change in slope of the sound speed vs density curve has been seen in mercury [5] at a density which is associated with electron localization [6].

The point at which our measurement technique becomes difficult also is very close to the expected thermodynamic critical point, and work is ongoing to find experimental ways of determining this point for refractory metals.

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