

# Heating liquid carbon to 7000 K with a cw laser

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Experiments demonstrate that condensed matter, in particular carbon, can be heated in a steady-state fashion to temperatures  $T \approx 7000$  K at an ambient gas pressure  $p \lesssim 10^8$  Pa under controlled conditions.

The heating of condensed matter to temperatures well above the melting points  $T_m$  of the most refractory elements and compounds at high ambient gas pressures is of significant interest in the physics of phase transitions and in certain applications. It would be particularly attractive to reach the vicinity of the critical points of these substances and to measure the physical properties of liquids in this range of properties ( $T > 5000$  K,  $p = 10^7$ – $10^9$  Pa).

Although it is generally believed<sup>1</sup> that these property values can be reached only by pulsed methods, e.g., those of Refs. 2 and 3, these methods run into several complications in attempts to determine unknown properties, in particular the temperature.

In the present letter we report an attempt to reach this part of the  $p$ - $T$  diagram through the steady-state heating of a sample by the focused beam from a rather high-power solid-state laser with a wavelength  $\lambda = 1.06 \mu\text{m}$  (Nd:YAG, 500 W). The pressure chamber holding the test sample is filled with an inert gas (He, Ne, or Ar) to a pressure of  $10^8$  Pa. The sample is then heated over a time interval usually amounting to several seconds. The temperature at the heating spot is measured by a special pyrometric apparatus capable of measuring brightness temperatures at the wavelength  $0.65 \mu\text{m}$  within an error of 3% at 7000 K. The radiation flux density at the heating spot reaches  $3 \times 10^4$  W/cm<sup>2</sup>. By choosing an appropriate geometry we were able to minimize the effect of the heated gaseous medium on the heating of the sample and on the temperature measurements. The heating of the gas near the surface gave rise to a random change in the gas density gradient and thus in the gradient of the refractive index. A point of fundamental importance in the choice of experimental geometry was the position of the window through which the laser beam entered and the temperature was measured. This window was nearly in contact with the heated surface of the sample, 2–3 mm away from it. This arrangement made it possible to guide the laser beam to the surface of the sample through the very inhomogeneous, dense gaseous medium essentially without scattering, and it permitted reliable measurements of the temperature at the heating spot by the optical method.

As a test substance we chose carbon (graphite), which has uniquely high properties at the graphite-liquid-vapor triple point:  $p_T = 10^7$  Pa and a temperature  $T_T = 4000$ – $5000$  K, according to different investigators. The critical properties of carbon are not known. Estimates based on a scaling theory<sup>4</sup> yield  $p_{cr} = 2.2 \times 10^8$  Pa and  $T_{cr} = 6800$  K.

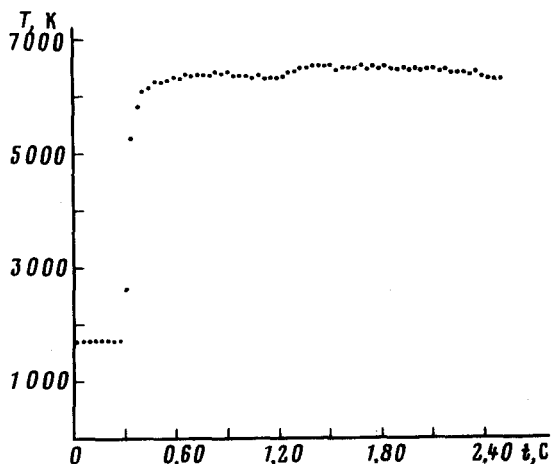


FIG. 1. Thermogram of the heating of a graphite sample in helium at a pressure of  $5 \times 10^7$  Pa.

At pressures above  $1.5 \times 10^7$  Pa, we found traces of molten carbon at the bottom of the crater resulting from the evaporation. These traces consisted either of droplets up to 1 mm in diameter, with a metallic luster, or flow regions on the crater walls. The large droplets at the bottom of the craters had a flat surface. Sections cut through the samples in a plane passing through the axis of a crater revealed a melting zone with an isotropic fine-grain structure with a crystallite size  $\approx 10 \mu\text{m}$ ; this structure differed sharply from the original layered structure of the pyrolytic graphite.

The resulting heating thermograms (Fig. 1) have a characteristic plateau, i.e., a region of a steady-state temperature, which corresponds to an intense evaporation of liquid carbon at the given external pressure. The temperature of this plateau depends on only the external pressure and ranges from  $\approx 5000$  K at a pressure of  $10^7$  Pa to  $\approx 7000$  K at  $10^8$  Pa.

Estimates show that the evaporation of the carbon which occurs under these experimental conditions is not far from equilibrium; i.e., there are no significant hydrodynamic effects at the liquid-vapor interface. The saturation vapor pressure of the evaporated carbon should be approximately equal to the pressure of the surrounding inert gas under these conditions. The results found in measurements of the plateau temperature as a function of the external pressure thus trace out the equilibrium line of the liquid and vapor phases of the carbon (the saturation line). The experimental data obtained here can be described by

$$\ln p, \text{ Pa} = (24.7 \pm 0.4) - (4.3 \pm 0.3) 10^4 \frac{1}{T, \text{ K}} \quad (T = 5000 - 7000 \text{ K}).$$

We used this expression to determine the latent heat of vaporization of liquid carbon:  $\Delta H_{\text{vap}} = 360$  kJ/mole. According to Ref. 4, the average number of atoms in a molecule of carbon vapor is about four in the temperature interval 5000–7000 K. For this value we find  $\Delta H_{\text{vap}} = 90$  kJ/(g-at C), in good agreement with the estimate<sup>4</sup>  $\Delta H_{\text{vap}} = 84$  kJ/(g-at C).

This heating method is not limited to research on phase transitions from a condensed phase to a vapor for the most refractory substances. We believe that there are other possible applications in the synthesis of refractory compounds at high pressures, in research on the phase diagrams of these compounds, in the laser processing of materials, etc.

<sup>1</sup>M. M. Martynyuk, *J. Phys. Khim.* **57**, 810 (1983).

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<sup>3</sup>G. R. Gathers, J. W. Shaner, and W. M. Hodgson, *High Temp. High Press.* **11**, 529 (1979).

<sup>4</sup>H. R. Leider, O. H. Krikorian, and D. A. Young, *Carbon* **11**, 555 (1973).

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