Experimental Results on Tungsten Wire Explosions in Air at Atmospheric Pressure - Comparison with a One-Dimensional Numerical Model[1]

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Abstract

Experimental results on exploding tungsten wires in air at atmospheric pressure at current densities $\geq 10^7$ A/cm^2 and a current rise $\geq 10^{10}$ A/s are presented. Besides the current through the probe and the Ohmic voltage across it, the diameter of the wire material and its surface temperature have been measured. The final aim of this investigation is the determination of thermophysical properties of higher-melting liquid metals up to its critical point. Here a first step should be made to prove the reliability of the methods and to justify crucial assumptions. To determine the limits of applicability of a homogeneous approach used so far, a one-dimensional numerical model in Z-pinch geometry has been used which gives the time evolution of the profiles of temperature, density and pressure across the wire.

As a matter of fact, the model describes well the main features observed in these experiments. Especially the physical cause of the maximum in the temporal dependencies of surface temperature is found out. This behaviour is related to some special thermodynamic properties of two-phase (liquid-gas) mixture forming in the peripheral layers of liquid metal. The temperature limit is determined up to which there are no remarkable radial distributions of temperature and density across the wire. The specific heat, the thermal expansion coefficient, and the electrical as well as thermal conductivity of liquid tungsten can now in principle be obtained. The parameters of the critical point of the liquid-vapour phase transition are also estimated.

KEY WORDS: critical point; electrical conductivity; evaporation; exploding wires; high temperatures; numerical modelling, refractory metals; thermal expansion; tungsten.

1. INTRODUCTION

To study thermophysical properties of metallic fluids of refractory materials up to critical-point conditions, due to the high values of critical temperatures it is necessary to generate the corresponding material states by pulse heating methods. As a first approximation, density and temperature of the expanding material can be determined from the expansion radius and from the pyrometrically measured surface temperature assuming a homogeneous density and temperature distribution over the cross section and a constant emissivity in the liquid. The pressure, however, has to be calculated using an adequate equation of state.

Using fast electrical discharges through wire-shaped probes of the studied material - so-called wire explosions - near-critical point conditions for tungsten have been reached. A critical discussion of the results has shown some discrepancies which could not be solved in the framework of a homogeneous model: A supposed vaporisation plateau similar to the well-known melting plateau has been found. The corresponding energy, however, was always too small to vaporise the whole material, and the corresponding (surface) temperature remains lower (7000 - 8000 K) than expected regardless of a strong increase of the energy input rate. At the end of the „vaporisation plateau“, the dE/dT value (the heat capacity) jumps to a very low value and afterwards the temperature passes a maximum between 12 000 and 14 000 K whereas the energy still increases.

These observations can be explained only in the case of a radial dependence of the quantities characterising the material state. A model has been used to describe the heating and subsequent expansion of the wire material which takes into account its electrodynamic, hydrodynamic, thermodynamic, and transport properties and an approximate equation of state for the fluid state including the liquid-gas phase transition.

2. EXPERIMENTAL SET-UP

Critical values for the liquid-gas phase transition of high-melting metals lie in a range around 10 000 K and 10 kbar. Whereas lower values can be obtained in high-pressure cells, such conditions can be reached only during fast wire explosions. If these explosions shall be carried out in an environment at atmospheric pressure, a very high rate of energy dissipation is necessary to reach high pressures in the material. This requires a steep increase of the current and a sufficient adaptation of the circuit impedance to that of the wire.

The fundamental design of the experiment is described in detail in [1]. A coaxial capacitor is surrounded by a copper tube. It is discharged through a spark gap into a wire which consists of the studied material (tungsten). The whole circuit without wire has a capacitance of 345 nF and an inductance of 57 nH.

The current is measured in two ways simultaneously: first by means of a coaxial shunt resistor and second by numerically integrating the signal of a Rogowski coil. Both signals fit to each other better than by 3 %. The numerically integrated signal was used for the further evaluations because of its better signal-to-noise ratio. The voltage is measured with a low-inductance ohmic divider. This signal also contains an inductive part which is proportional to the derivation of the current. More than 90 % of this is compensated by a small coil that is connected anti-parallel to the voltage divider. The remaining part is then numerically corrected in a way that the cold resistance of the sample is fitted best. The dissipated energy and the resistance are calculated from the so determined current and ohmic voltage.

The diameter of the expanding wire is taken from a streak image caused by the self-luminosity of the heated wire. For each time, the distance of the maximum derivations of brightness is determined and taken for the diameter. This method is reasonable due to the sharp jump of temperature at the surface. From the start up to the end of melting the self-luminosity is small therefore the results from [2] are used here.

Shadowgraphs are not useful because the wire is surrounded by a thin isolating layer to avoid surface discharges.

The surface temperature of the sample is determined from the radiation at 650 nm. A spot with a diameter of 15 µm is displayed on the entrance of a fibre which is connected with a Si-PIN diode. In the diode signal the melting plateau is identified and used for a self-calibration of the pyrometer. Assuming the emissivity being constant during the following process a surface temperature can be calculated in a first approximation from the radiation signal using Planck´s law.

The whole wire is observed during the explosion with a fast framing camera. Four images with an exposure time of 10 ns each ensure that no parallel discharges and no change of length of the wire occur during the observation time. In addition, they allow to judge the homogeneity of the sample and the relevance of temperature and radius determination.

Important for passing the critical region during a wire explosion is the selection of an appropriate specimen. Its resistance has to match the impedance of the discharge circuit, and its mass has to be evaporated during the first half period of the discharge. Its radius has to be smaller than the skin depth, and special care has to be taken to prevent parallel surface discharges. The used circuit has a natural frequency of about 1.2 MHz and an impedance of about 0.3 Ω. The skin depth for tungsten is then about 110 µm so that in a stationary case the wire with a diameter of 37.5 µm not affected. The dynamic skin effect leads to a relaxation time of some 10 ns and has therefore to be considered only before melting. With a length of 5.0 mm the cold resistance of 83 mΩ (measured) matches well, and the mass could be evaporated twice with the maximum supplied energy.

The time for levelling out small pressure differences should be small compared with the experimental time scale. Using a sound speed of 4 kms^{-1} the time for crossing the radius is about 10 ns.

Clean tungsten wires show strong surface discharges at surface temperatures above 6000 K. An oxidized surface diminishes this effect due to the higher work function of tungsten oxide. Best results were obtained with wires coated with polytetrafluorethylene (PTFE). The fluor accepts the thermally emitted electrons in such an amount that the observation times can be extended beyond the time of passing the critical region. Thus tungsten wires (length 5.0 mm, diameter 75 µm with a transparent coating of 20 µm PTFE [3] were used.

3. THEORY

To describe the motion of material and distributions of electric and magnetic fields during the pulse heating process, a one-dimensional magnetohydrodynamic model in Z-pinch geometry [4, 5] is used. In this geometry, the velocity of the material has only a radial component u, the electrical current density has only a component along the axis j, and the magnetic field strength has only an azimuthal component H. For this case the laws of conservation of mass, momentum, and energy can be written as

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u) = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{jH}{c\rho}, \tag{2}$$

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial r} = \frac{jE'}{\rho T}, \tag{3}$$

where ρ, p, and T are the density, pressure and temperature, respectively, and s is the specific entropy. All the variables are functions of the radius vector r and the time t. The electric field strength E' in the reference frame which is in rest in relation to the material particles can be calculated from Lorentz formula $E' = E + uH/c$ (E is the electrical field strength in the laboratory frame of reference, and c is the speed of light in vacuum).

The boundary conditions for the system of Eqs. (1 - 3) were derived in [6]. The task about the evaporation of a metal from the surface of a sample heated by a high-

density electrical current pulse (j ~ 10^7 A/cm^2) was solved. The following expressions for the pressure and the temperature on the sample surface were obtained

$$p(a,t) = 0.56\, P_{st}(T(a,t)), \tag{4}$$

$$T(0,t) \approx T(a,t) + \frac{B}{j}\exp[R\lambda_0 / T(a,t)], \tag{5}$$

where $a = a(t)$ is the radius of the sample, P_{st} is the saturated vapour pressure, R is the molar gas constant, λ_0 is the molar heat of evaporation at $T = 0$ K, and B is a function weakly depending on T in the temperature interval $T < 0.9\, T_c$ (T_c is the critical temperature of the liquid-gas phase transition).

The system of equations for the total current in a RCL circuit containing the wire can be written as

$$\frac{L_0 + L}{c^2}\frac{dI}{dt} + \frac{I}{2c^2}\frac{dL}{dt} + E(a,t)l + U_c = 0, \tag{6}$$

$$\frac{dU_c}{dt} = I / C_0, \tag{7}$$

where L_0 and L are the inductance of the circuit and the wire, respectively, U_c is the capacitor bank voltage , and C_0 is the capacitance.

The initial conditions for the task are as follows: p = 1 bar, T = 300 K, $U_c = U_0$, and I(0) = 0. To make the set of equations to be completed, we need the equation of state, i.e. the dependencies $p(\rho, T)$ and $s(\rho, T)$, and the electrical conductivity $\sigma(\rho, T)$.

The equation of state used for the calculations was a so-called soft-sphere equation [7]; the main reason for using it was its simple form and its successful application to expanded metals [8]. It was further modified in [9]. An additional fitting parameter was introduced to describe the data on expanded liquid transition metals.

The free energy for this equation of state is

$$F = E_0(\rho) + F_i(\rho, T) + F_r(\rho, T) \tag{8}$$

where E_0 is the attractive part, F_i is the ideal gas contribution, and F_r is the repulsive

soft-sphere contribution.

$$E_0 = \frac{R\Theta}{\mu}(C_n x^{n/3} - x^m), \tag{9}$$

$$F_i = -\frac{R\Theta}{\mu} y[\ln(y^{3/2}/x) + const], \tag{10}$$

$$F_r = \frac{R\Theta}{\mu}\frac{Q(n+4)}{2} x^{n/9} y^{2/3}; \tag{11}$$

here the variables $x = \rho/w$, and $y = \rho/T$ are used (μ is the molar weight). The equation of state contains five fitting parameters : w, ρ, m, n, and Q. The parameters were chosen in the liquid phase to reproduce the experimental values of the densities near the melting and near the boiling point at atmospheric pressure, the heat of evaporation at the boiling temperature, the thermal expansion coefficient , the sound velocity, and the isobaric specific heat in the temperature range 4000 - 7000 K.

To satisfy all the conditions, it was necessary to introduce one fitting parameter more: instead of the ideal gas specific heat value 3/2 we use in the ideal gas term (Eq.(10)) the fitting parameter c_v.

The electrical conductivity in a wide area of the phase diagram of tungsten (solid, liquid, plasma, and gas) was obtained on the basis of some theoretical models and approximations of an experimental data set [10]. In the two-phase liquid-gas region the conductivity was calculated according to the effective medium formula [11].

The Godunov method was used to solve the hydrodynamic part of system of Eqs. (1) - (3) [12]. Maxwell´s equations (6) - (9) were solved by the tridiagonal inversion method [13].

4. DISCUSSION

In Fig. 1, the temporal dependencies of electrical data in the experiment and the corresponding curves given by the model can be seen; the agreement is remarkable.

Fig. 2 shows the time development of the temperature: the pyrometrically measured surface temperature of the sample and the calculated temperatures for different radial layers of the sample. For the experimental curve as well as for curves representing the outer layers a maximum is observed. It should be noted that the energy input continues to increase even after the maximum (see Fig. 1). This behaviour of the temperature of the outer layers is caused by a rapid expansion of the two-phase mixture appearing in these layers. Therefore this temperature maximum is a sign for reaching the vapour-pressure curve at least by part of the material (this was intuitively presumed already earlier [14]). The stronger increase of the experimentally determined temperature at $T > 8000$ K could be faked by an increase of the emissivity due to the generation of bubbles in a small layer on the surface. As one can see, a homogeneous distribution of the temperature across the area of the sample can be assumed up to a surface temperature $T \leq 10{,}000$ K.

In Fig. 3, the V-T diagramm can be seen. In the model the inner part of the material passes the critical density above critical temperature as an one-phase fluid. The outer part passes below the critical temperature forming a two-phase layer. Due to the extremely low sound speed in this layer, the core may reach the required pressure.

The experimentally determined temperature which characterizes a layer near the surface should be corrected above 8 000 K due to a presumedly increasing emissivity. Its maximum should not exceed the critical temperature.

It seems to be possible to describe main features of the studied wire explosion with the used model. This gives confidence in future applications to the complex processes during the fast heating of refractory metals up to critical parameters.

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FIGURE CAPTIONS

Fig. 1: Electrical data (current I, dissipated energy e, and resistance R): the full lines show the experimental values for a capacitor voltage of U_c = 4.6 kV; the dashed lines show corresponding model calculations.

Fig. 2: Temperature versus time; the full line gives the pyrometrically measured surface temperature of the sample. The dashed lines are temperatures of consecutively following layers from the model calculations.

Fig. 3: Volume versus temperature; V_0 is the initial volume of the solid. The full line gives the experiment. The dashed lines are from model calculations; the different radial layer are indicated. The dotted curve is the boundary of the coexistence region; the critical point is shown (c.p.).

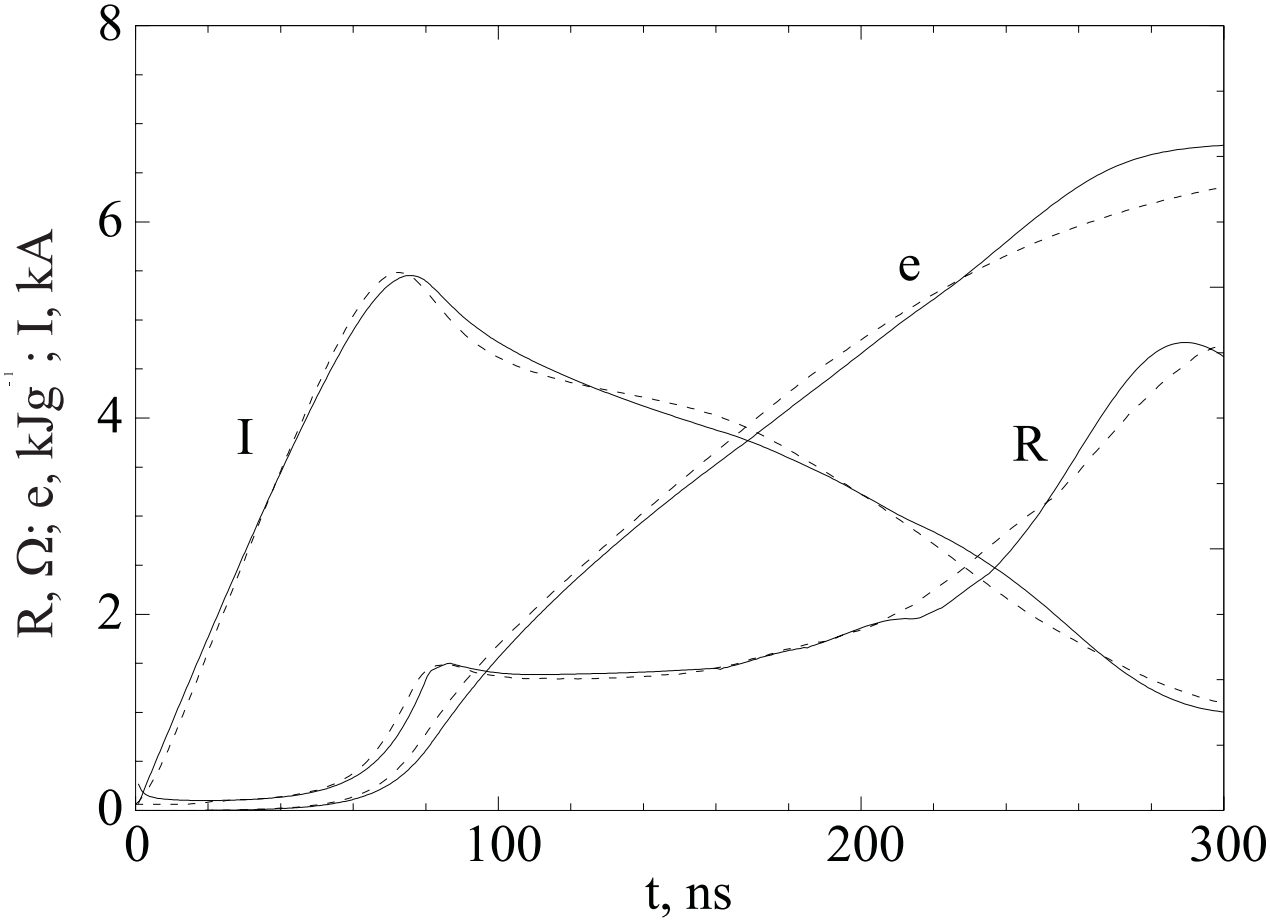

FIGURE 1

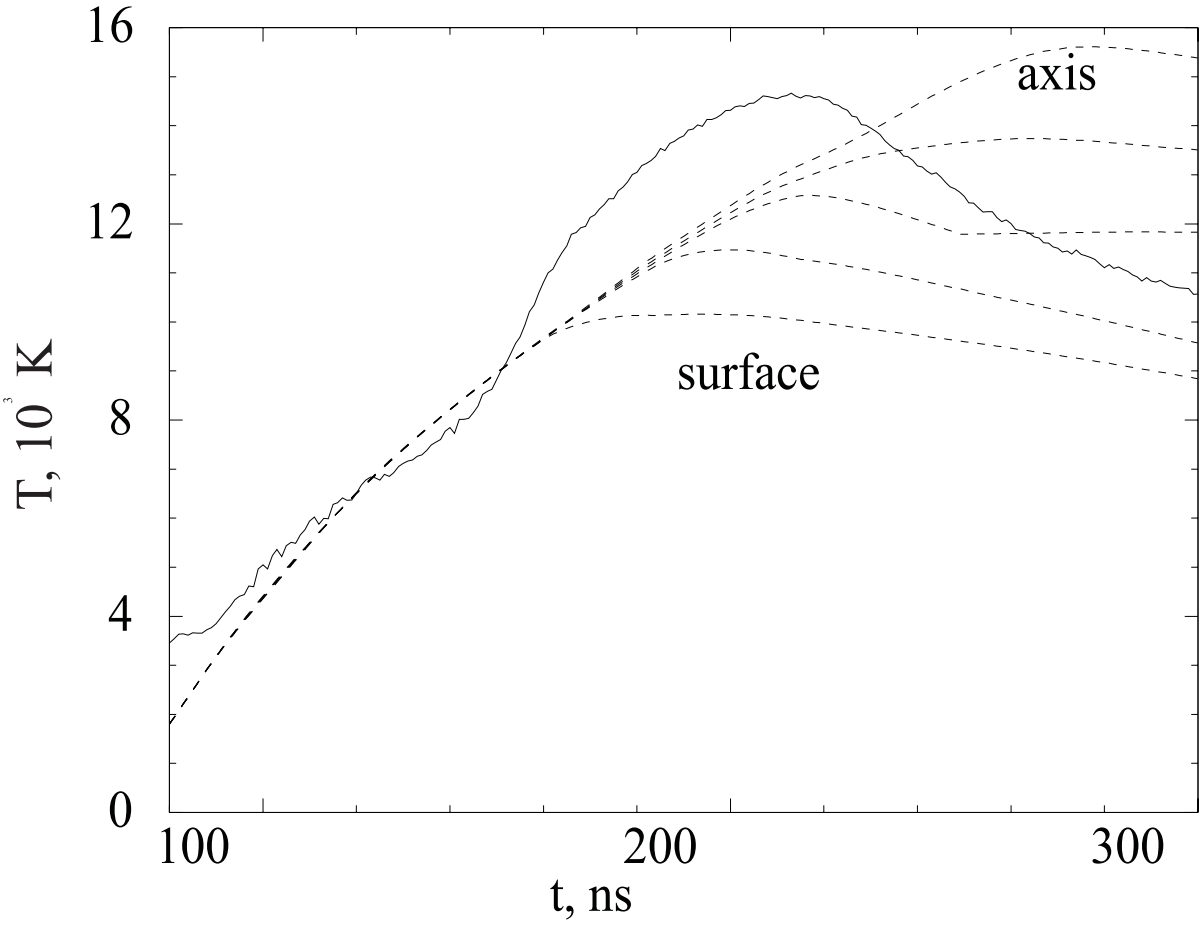

FIGURE 2

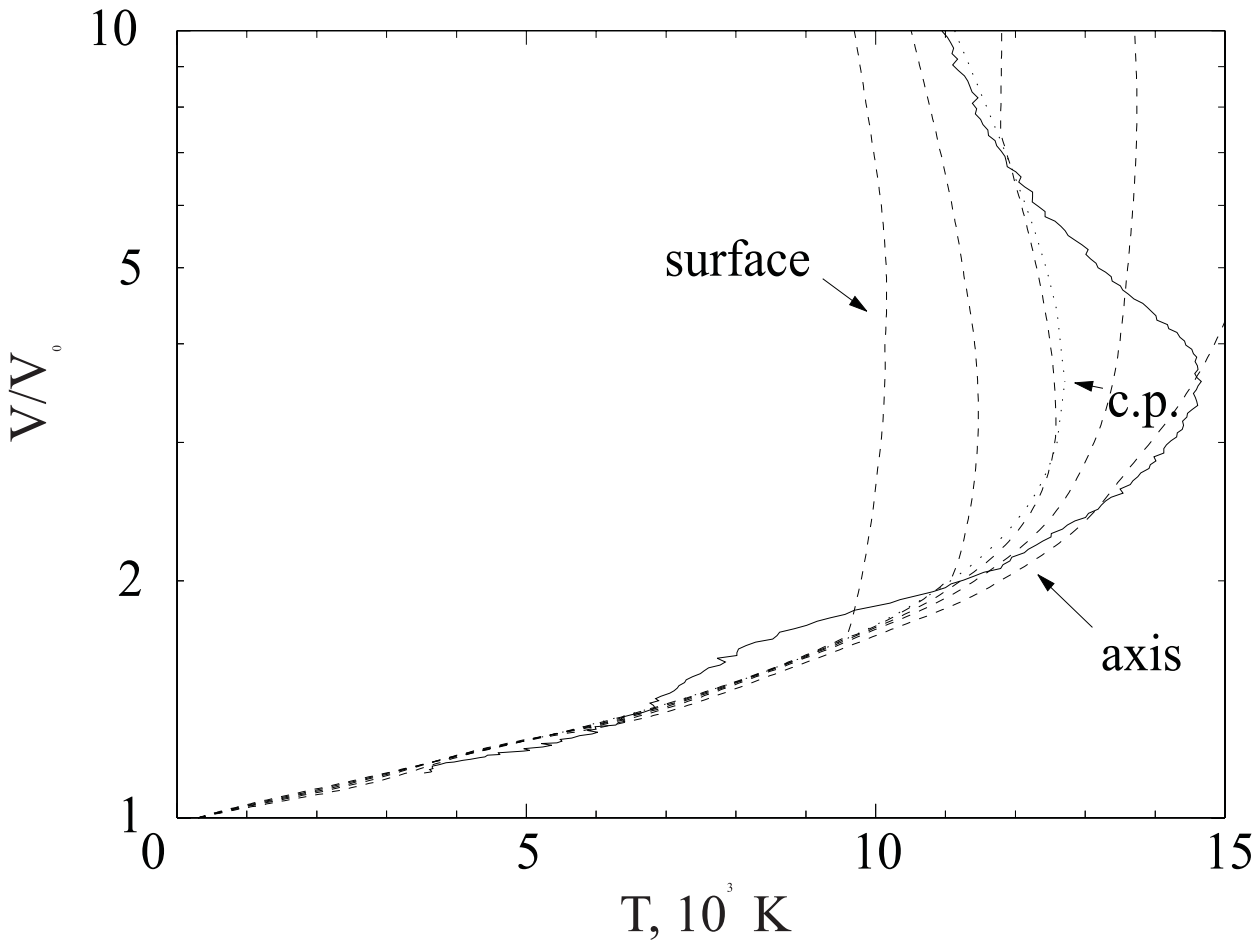

FIGURE 3